ADVANCED PHYSIOGRAPHY

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ADVANCED

PHYSIOGRAPHY

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PREFACE.

THIS book has been prepared at the request of a number of teachers of Physiography. It is supplementary to my 'Elementary Physiography,' and is very similar in structure, and the arrangement follows pretty closely the lines laid down in the Syllabus of Advanced Physiography of the Science and Art Department. Though many of the subjects treated in the first two chapters are not directly included in the syllabus, the questions set from time to time indicate that the examiners require candidates to have a knowledge of them. Indeed, a knowledge of astronomical instruments, and the principles underlying their construction, is essential for a proper understanding of the results attained.

Some of the facts herein contained are founded upon notes taken during Prof. Lockyer's lectures on Astronomical Physics at the Royal College of Science. Young's comprehensive 'General Astronomy,' and Miss Clerke's 'History of Astronomy of the Nineteenth Century' have also been referred to, most of the numerical quantities concerning the solar system having been derived from the former source. A few portions are reprints of articles contributed by me to various journals. Thus, the latter half of Chapter V. appeared in *Nature*, May 23rd, 1889, under the title 'The Determination of Masses in Astronomy,' and is founded upon an article by Mons. Tisserand in the *Annuaire du Bureau des Longitudes* (1889). Similar levies have been made upon *The Practical Teacher* and *Science and Art.*

The majority of the illustrations have been specially drawn for the book. In addition to these, Messrs. T. Cooke and Sons, the well-known telescope makers of York, have kindly permitted the use of illustrations of some of their instruments, and a few illustrations have been purchased from Messrs. Cassell and Co. Specific acknowledgment of other sources is made in the course of the book.

Finally, thanks are due to Mr. Barker North, A.R.C.S., for kindly reading and correcting the section dealing with astronomical matters while the book was passing through the press.

RICHARD A. GREGORY.

BUT for the fact that the small portion of the book that can be considered to belong to the domain of Geology covers some rather difficult and very debatable ground, and treats of matters about which much diversity of opinion exists, allusion to it in the preface scarcely seems necessary. As will be apparent from many of the facts and references regarding underground temperature, I have availed myself of French and German sources of information: De Lapparent, Carl Vogt, Credner, &c. With regard to the Interior of the Earth, I have adopted the line of argument so ably advocated by Prestwich in his highly philosophical and classical treatise on Geology, supplementing it, however, by some arguments of my own. The style I have adopted is somewhat different from that of class books generally, in which condensation of information is mainly aimed at, but this is largely due to the fact that the subjects treated are, to a great extent, speculative.

JAMES C. CHRISTIE.

April, 1893.

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ADVANCED PHYSIOGRAPHY.

CHAPTER I.

THE PRINCIPLES OF LIGHT.

Luminous and Non-Luminous Bodies.—A self-luminous body is one which shines by its own light, for example, the sun, stars, and a gas-flame. Bodies which only become visible when the sun or some other source of light is shining upon them are non-luminous. The moon belongs to this class. As everyone knows, the great source of our light and heat is the sun. Compared with it, all other sources sink into insignificance. The light of the full moon, which can truly be said to be nothing but second-hand sunlight, is about $\frac{1}{600,000}$ that of the sun, and the light received at any one place from all the stars, visible and invisible to the naked eye, cannot be much more than $\frac{1}{30,000,000}$ the intensity of sunlight. With the exception of some luminosities produced by electrical action, all our artificial sources of light are the result of chemical changes, water and carbon dioxide being generally the chief products of the combustion which goes on.

Temperature and Luminosity.—It by no means follows that different bodies emit the same amount of light when at the same temperature. A spiral of platinum wire soon becomes incandescent in the non-luminous flame of a Bunsen burner or blow-pipe, though the flame and wire have the same temperature. Another illustration of the same fact is afforded by the lime-light. In this case the high temperature produced by the combination of hydrogen and oxygen is utilised. The flame which results from the chemical action is almost invisible, but by making it impinge upon a cylinder of lime, a brilliant white light is produced, the lime becoming white hot. Powders dropped through a

colourless flame are rendered incandescent, and it can be understood that if a stream of powder is kept up, the flame would acquire luminosity owing to the incandescence of the particles passing through it. Similarly, the flames of an ordinary gas jet or candle are luminous on account of the incandescence of the carbon particles set free when combustion occurs. The existence of such particles is proved by holding a cool surface, such as a plate, over the flame. The plate becomes blackened owing to the deposit of carbon cooled below the temperature at which they are rendered incandescent.

Theories of Light.—According to Newton, self-luminous bodies emit particles which, by bombarding themselves upon the eye, produce the sense of vision. There are many serious objections to this *emission theory*, and it is now entirely discarded. The *wave theory* of light assumes the existence of a weightless or imponderable medium termed *ether* in which luminous vibrations take place. This medium is supposed to be everywhere and in everything, and waves of light are transmitted through it in somewhat the same way that waves of sound travel through the air. This theory was established by experimentally proving that light moved slower in water than in air. If the emission theory were true, the reverse would be the case.

Propagation of Light.—Light proceeds in straight lines and in all directions from a luminous body. This principle is illustrated by means of three screens, in each of which a small hole has been punched. When the screens are arranged so that the holes are in a straight line, an object can be viewed through them, but a slight shift of one of the screens is sufficient to render it invisible. The fact that it is impossible to see round a corner without some reflecting device also shows that light is propagated in straight lines.

Intensity of Light.—The intensity of light upon any surface varies inversely as the square of the distance of the surface from the luminous body. Consider the light which leaves a luminous body at a particular instant; then, since it proceeds in all directions, after it has travelled a distance of one foot, it will be spread over the surface of a sphere of one foot radius; at a distance of two feet from the luminous centre, a spherical surface having a radius of two feet would be illuminated, and so on for any other distance, the radius of the sphere of illumination being equal to the distance from the light source. Now if the same quantity of light

is spread over two surfaces, one having twice the area of the other, the larger will only appear half as bright as the smaller; in other words, the relative brightnesses are inversely proportional to the surfaces. But the surfaces of spheres are in the proportion of the squares of their respective radii. Hence the brightnesses are inversely proportional to the squares of the radii, that is, inversely as the square of the distance from the luminous centre. This result is arrived at algebraically as follows:—

Let r and R = radii of two spheres of illumination, and let $R = 2r$.

Then area of sphere with radius $r = 4\pi r^2$.

And area of sphere with radius $R = 4\pi R^2 = 4\pi (2r)^2$

$= 16\pi r^2$

Hence the areas of the two surfaces are to each other as

$$4\pi r^2 : 16\pi r^2$$

That is :: 1 : 4, or as the squares of the radii.

The light waves, in travelling the distance R, do not decrease in power, but they have to act over four times the area, and therefore produce one quarter the effect.

The Velocity of Light.—Several determinations have been made of the rate at which light travels. The first result was obtained about 1670 by observations of the difference between the observed and calculated times of eclipses of Jupiter's satellites. The discovery of astronomical aberration by Bradley opened up another method for determining the velocity of light. The aberration constant is found by measurement to be $20''.49$, and this angle gives the ratio of the velocity of the earth in its orbit to the velocity of light. Computation shows that the ratio is as one is to about ten thousand, that is to say, light travels about ten thousand times faster than the earth. Knowing the earth's period of revolution, its orbital velocity is easily found when the sun's distance has been accurately determined, hence the velocity of light can then be estimated.

Thus, if V represent the velocity of light, and v the earth's orbital velocity, we have the proportion:

$$V : v :: 10{,}089 : 1$$

$$\text{Whence } V = v \times 10{,}089 = 18{\cdot}5 \times 10{,}089$$

$$= 186{,}600 \text{ miles per second.}$$

Both this method and that of Jupiter's satellites depend upon our knowledge of the sun's distance, so the results obtained by the use of either must be changed as different values for the solar parallax are accepted.

Fizeau's Determination of the Velocity of Light.—In 1849 Fizeau devised a means by which the velocity of light could be determined on the earth without any astronomical observations whatsoever. Two stations were chosen, separated by a distance of $5\frac{1}{2}$ miles. The problem was to determine the time taken by a beam of light to travel from one station to the other and back again. At one station a powerful light was placed behind a screen having two holes in it. In front of the screen a toothed wheel could be caused to revolve, and the arrangement was such that when one tooth appeared in front of one hole the tooth at the other end of the diameter was in front of the second hole. In like manner, the two holes were uncovered at the same instant of time as two spaces passed in front. A mirror was placed at the second station and fixed so that a beam of light which started from hole number one would be reflected back to hole number two, behind which was a small telescope. The wheel was set in such rapid motion that when the reflected beam arrived at the second hole a tooth blocked its way. By doubling the speed of the wheel, the space succeeding that diametrically opposite the one through which the beam had been sent could be brought in front of the second hole. If light travelled instantaneously, the reflected beam would appear at the second hole, and be seen in the telescope at the same instant that it left the first one. But observation proved that this was not the case. The reflected beam could be totally or partially eclipsed, and by noting the speeds necessary to produce these different appearances the time taken by light to traverse twice the distance between the two stations could be calculated. Fizeau used a wheel having 720 teeth, and found that 12·6 revolutions per second shut off the reflected beam from the viewing telescope. And since the spaces between the teeth were of the same size as the teeth, the time taken by a tooth to pass over a distance equal to its own width is

$$\tfrac{1}{2} \text{ of } \tfrac{1}{720} \text{ of } \frac{1}{12{\cdot}6} \text{ of a second, or } \frac{1}{18{,}144} \text{ of a second.}$$

The distance between the two stations was $5\frac{3}{8}$ miles, hence the distance travelled by the beam was $5\frac{3}{8} \times 2 = 10\frac{3}{4}$ miles. Hence the velocity of light is $10\frac{3}{4} \times 18{,}144$ miles per second, that is,

186,700.

195,000 miles per second. This result is no doubt in excess of the truth, owing probably to the fact that it is very difficult to say exactly when the reflected beam is eclipsed. The method is most

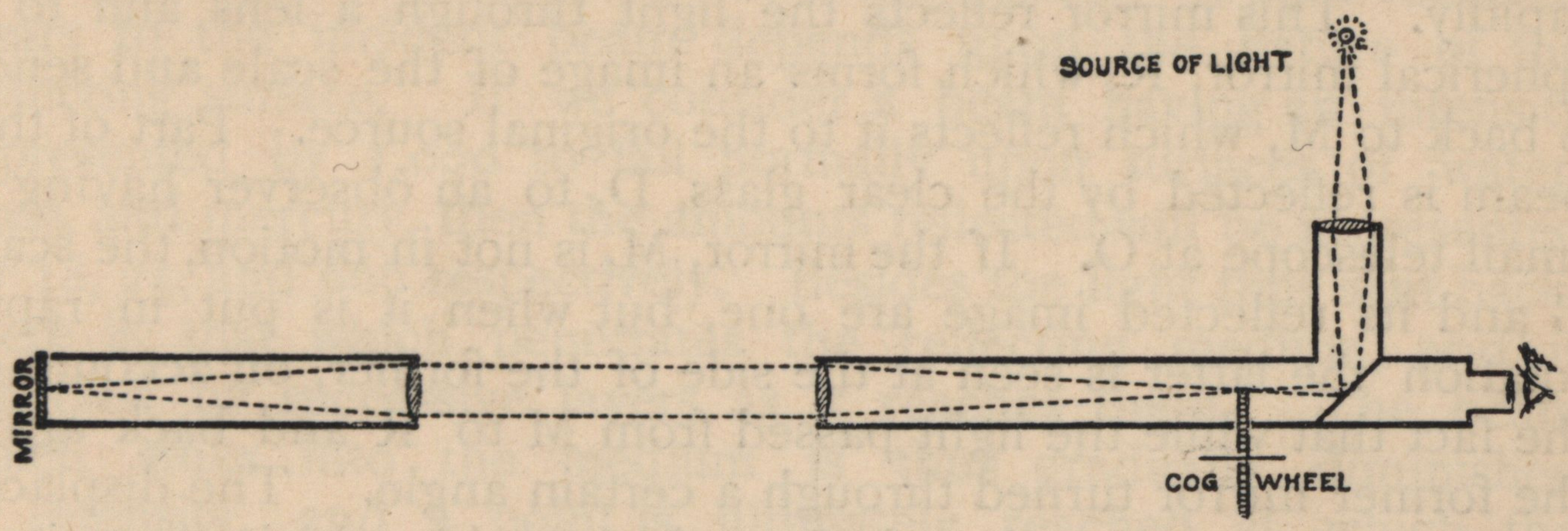


Fig. 1. Fizeau's method of determining the Velocity of Light.

interesting, as it was the first which gave any idea as to the velocity with which light travels on the earth's surface. (Fig. 1.)

Foucault's Determination of the Velocity of Light.—Another French investigator named Foucault invented an arrangement whereby the velocity of light can be found in the space or an ordinary room. The apparatus is illustrated by Fig. 2. A

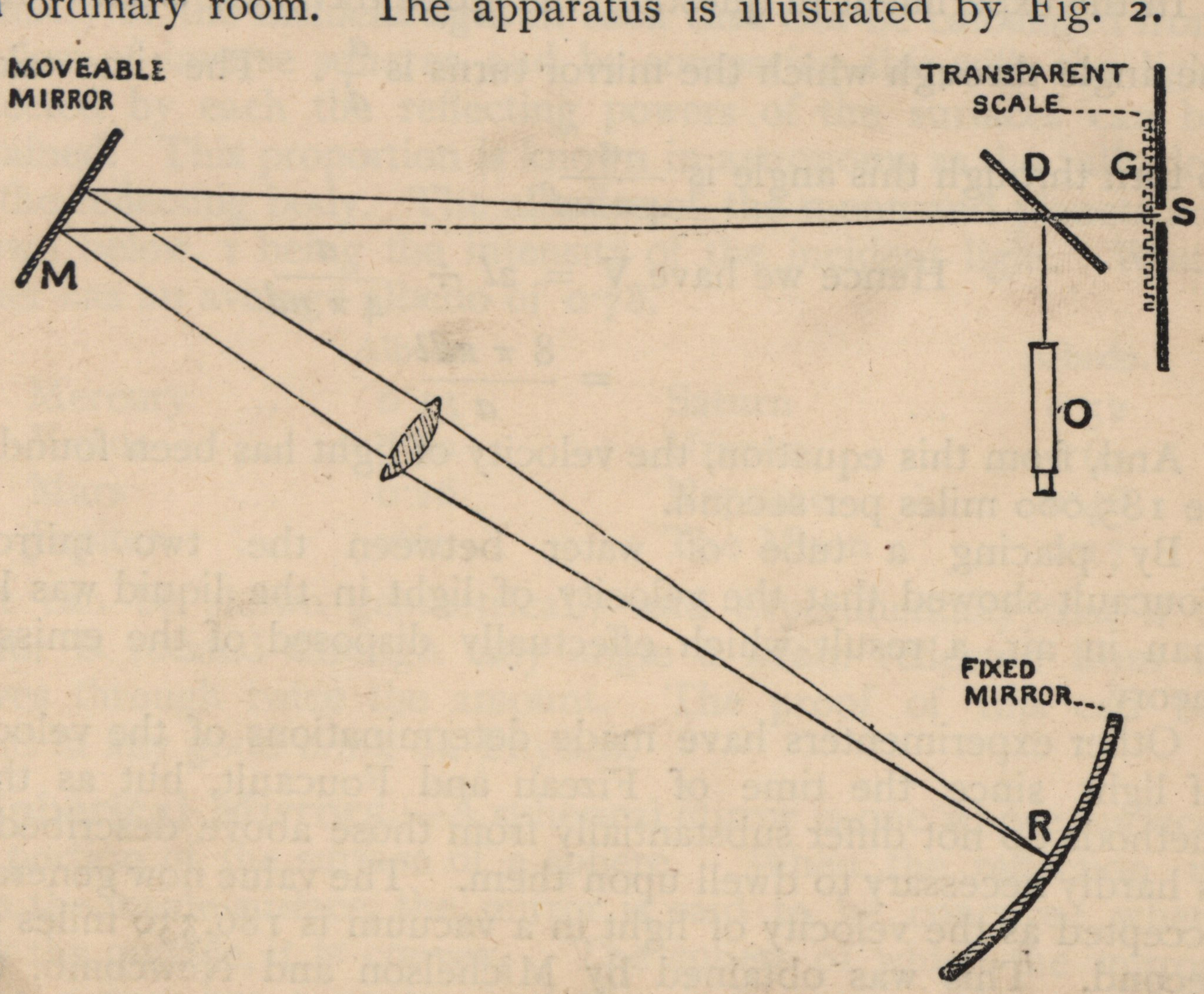


Fig. 2. Method of determining the Velocity of Light.

beam of light passes through a hole in the screen, S, then through a transparent glass scale, G, and a plane glass mirror at an angle of 45°, D, to a mirror, M, capable of being whirled round very rapidly. This mirror reflects the light through a lens and to a spherical mirror, R, which forms an image of the scale and sends it back to M, which reflects it to the original source. Part of this beam is reflected by the clear glass, D, to an observer having a small telescope at O. If the mirror, M, is not in motion, the scale G and its reflected image are one, but when it is put in rapid rotation the latter is seen at the side of the former, on account of the fact that while the light passed from M to R and back again the former mirror turned through a certain angle. The displacement can be measured and the velocity with which the mirror rotates can be found. Let a be the displacement; d, the distance from the glass scale to the moveable mirror; n, the number of revolutions of the mirror per second; l, the distance from M to R, and t, the time taken by light to traverse this distance.

$$\text{Now velocity V} = \frac{\text{space travelled}}{\text{time taken}}.$$

In the experiment in question the space traversed is $2l$. And the angle through which the mirror turns is $\frac{a}{d}$. The time taken to turn through this angle is $\frac{a}{4\pi nd}$.

$$\text{Hence we have V} = 2l \div \frac{a}{4\pi nd}$$

$$= \frac{8\pi ndl}{a}$$

And, from this equation, the velocity of light has been found to be 185,000 miles per second.

By placing a tube of water between the two mirrors, Foucault showed that the velocity of light in the liquid was less than in air, a result which effectually disposed of the emissive theory.

Other experimenters have made determinations of the velocity of light since the time of Fizeau and Foucault, but as their methods do not differ substantially from those above described, it is hardly necessary to dwell upon them. The value now generally accepted as the velocity of light in a vacuum is 186,330 miles per second. This was obtained by Michelson and Newcomb, two American scientists.

Reflection of Light.—When a ray of light falls upon a reflecting surface it is found that the reflected ray makes the same angle with the normal as the incident ray, and that both are in the same plane. The proportion which the quantity of light reflected bears to the incident beam depends upon the nature of the reflecting surface. If we consider a beam having an intensity represented by 1,000 to fall normally upon surfaces of water, glass, and mercury, then the amounts reflected will be represented by 18, 25, and 666 respectively. Besides the light thus sent back, there is that which penetrates the reflecting medium, and is reflected by successive layers as it reaches them. The beam which sinks into the medium is thus gradually diminished in intensity, and a point is ultimately reached at which the beam is so faint that no light is reflected. The light sent back from the extreme surface of a reflector is of the same colour as the incident beam, but that which sinks into the medium and then travels back through the medium to the eye suffers absorption, and its colour is thereby changed. It has been previously stated that the moon and planets shine by reflected light, and knowing the distances of these bodies from the sun, the intensity of the incident light in each case can be calculated from the law of inverse squares, and by comparing this with the light reflected by each the reflecting powers of the surfaces can be obtained. This proportion is known in astronomy as the 'albedo' of the reflecting body. The albedos of the moon and planets are shown below, 1 being the intensity of the incident light. White paper has an average albedo of 0·78.

	Albedo.		Albedo.
Mercury ...	0·13	Saturn ...	0·52
Venus ...	0·50	Uranus ...	0·64
Mars ...	0·26	Neptune ...	0·46
Jupiter ...	0·62	The Moon ...	0·17

It can be shown geometrically and experimentally that if a mirror is rotated through any angle a beam reflected from it moves through twice the amount. The proof of this can be found in any good book on Physics.

Spherical Mirrors.—A spherical mirror is one whose surface is a portion of the surface of a sphere. When the reflection is from the inside surface, the mirror is said to be concave; when from the outside, it is convex. The sphere of which the mirror forms a part has a centre, and this is known as the *centre of*

curvature of the mirror. If the sun's rays are allowed to fall upon a spherical mirror, an image of our luminary is formed at a certain distance in front of it. The rays are parallel on account of the enormous distance of the sun, and the point to which they are concentrated is termed the *principal focus* of the mirror. This point is half-way between the centre of curvature and the reflecting surface, and its distance from the latter is termed the *focal length* of the mirror. The directions of the rays by which a mirror forms an inverted image of a distant object, are shown in Fig. 3. Lines

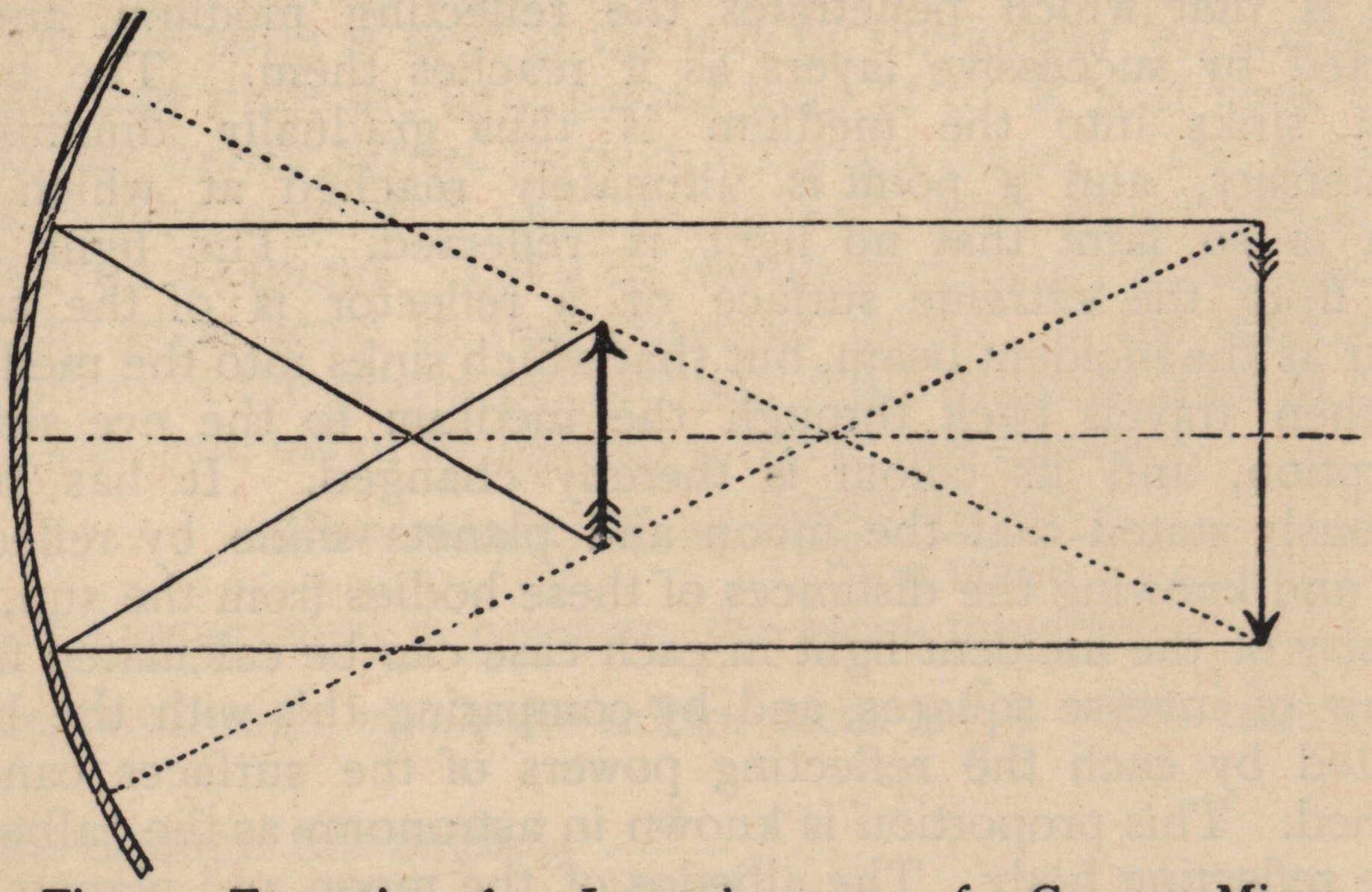


Fig. 3. Formation of an Image by means of a Concave Mirror.

are drawn from the object through the centre of curvature to the mirror. Parallel rays fall upon the mirror, are reflected to a focus, and the reflected rays produced to the secondary axes, locate the position of the image. As a matter of fact, a spherical mirror is incapable of bringing all parallel rays to one focus. The mirrors which can accomplish this are parabolic in form, that is, they are portions of the surfaces of paraboloids instead of portions of spherical surfaces.

Refraction of Light.—In general, when light passes from any medium to one less dense it is bent or refracted out of its original direction. Thus, when a stick is thrust slantingly into water the portion under water appears to be bent towards the surface. In this case the light from the under portion passes from the water to a less dense medium—the air. Conversely, when light passes from one medium to a denser it is bent in the opposite direction. The perpendicular to the point where the light leaves

one medium and enters another is termed the normal. The laws of refraction are stated as follows:—

(1.) The incident ray, the normal, and the refracted ray all lie in one plane.

(2.) The ratio of the sine* of the angle of incidence to the sine of the angle of refraction is a constant quantity so long as the media from and to which the light is passing remain the same. If the media are *a* and *b*, this quantity is equal to the refractive index from *a* to *b*.

(3.) The refractive index of a body is the value of the constant which would be obtained if light were passing from a vacuum. In passing from a less dense to a more dense medium the refractive index is always greater than unity.

Atmospheric Refraction.—The atmosphere surrounding our earth diminishes in density as we ascend, hence its refractive power diminishes from the earth's surface to the outer limit. In consequence of this we do not see the heavenly bodies in their true position except when they are in the zenith. The rays of light from these objects are continually passing from rarer to denser layers, and are therefore bent towards the normal to the surfaces of separation, the result being that the path traversed is curved, with the concave side towards the earth. (Fig. 4.) In the illustration AS represents the direction in which the star, S, would be seen if the earth had no atmosphere, and AS′ the direction in which it is really seen. The difference between the two directions is termed astronomical refraction. A star at the zenith, Z, is seen in its true direction, AZ, and to an observer situated at the earth's centre refraction would always be *nil*. It should be evident from the illustration that refraction always makes a star appear higher in

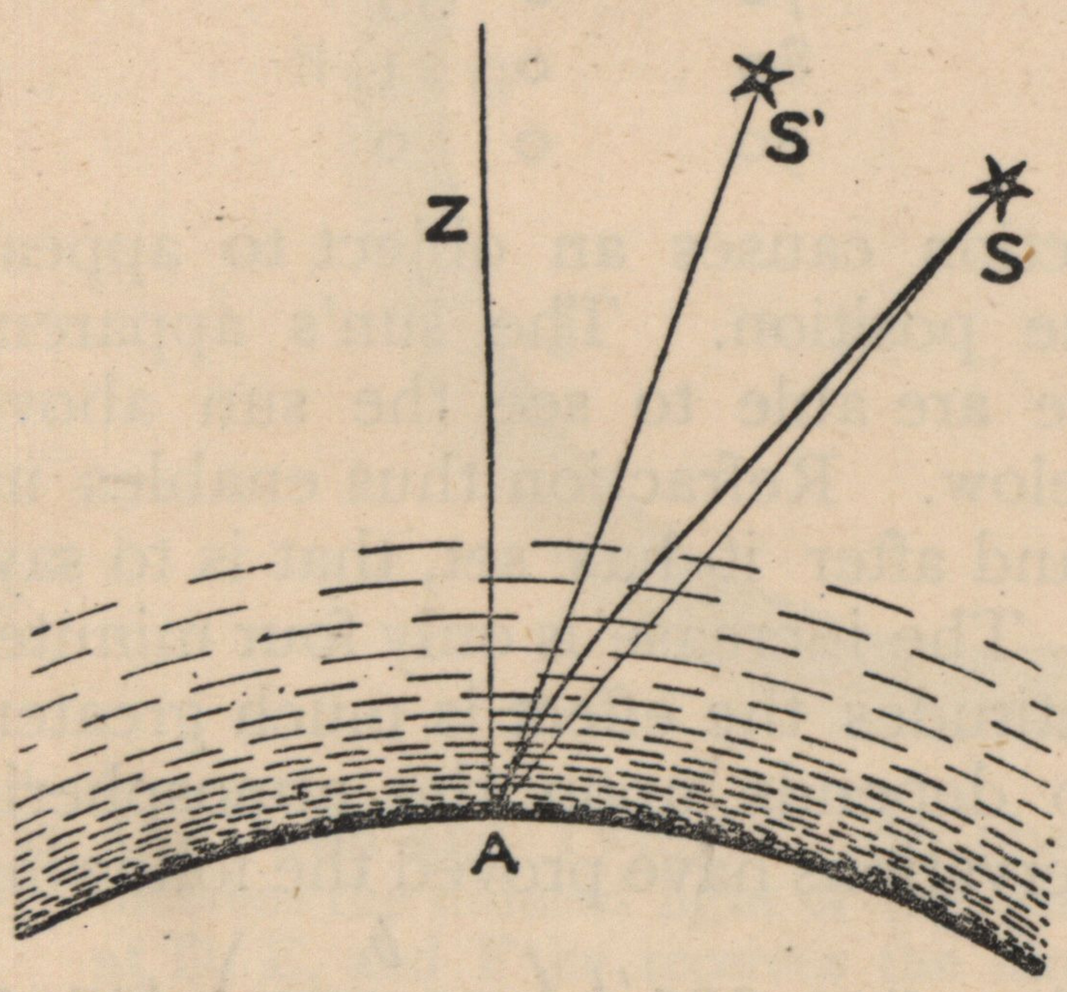


Fig. 4. Effect of refraction upon the apparent position of a star.

* Students unfamiliar with trigonometrical ratios will find them explained on page 63.

the sky than it really is; in fact, we get the following relations:— True zenith distance = apparent zenith distance + refraction. True altitude = apparent altitude — refraction. Tables are constructed for the use of astronomers, showing the value of refraction at different altitudes. It is assumed for purposes of computation—

(1.) That the thickness of the atmosphere is very small compared with the earth's radius.

(2.) That the atmosphere is made up of a large number of concentric strata, each denser than the one above it, but itself of uniform density. The following table shows the angles which have to be subtracted from a few apparent altitudes to obtain the true altitude of a celestial object:—

Altitude	Refraction	Altitude	Refraction
0°	34′ 54″	40°	1′ 38″
2	18 9	50	1 8
4	11 39	60	0 48
10	5 15	70	0 33
20	2 35	80	0 21
30	1 38	90	0 0

On the horizon, then, refraction causes an object to appear nearly 35′ higher than its true position. The sun's apparent diameter is about 32′, hence we are able to see the sun above the horizon when it is really below. Refraction thus enables us to see the sun before it rises and after it has set, that is to say, increases the length of the day. The increase is only four minutes at the equator, but in higher latitudes the effect is much greater. The amount of refraction also depends upon the atmospheric pressure and temperature. Obervations have proved the following equation for finding refraction— $r = 992'' \left(\frac{b}{460 + t}\right) \tan z$, where r represents the refraction in seconds of arc, b the height of the barometer in inches, t the temperature on the Fahrenheit scale, and z the apparent zenith distance.

Twilight and Dawn.—If there were no atmosphere, as soon as the sun had sunk beneath the horizon a place would be shrouded in darkness. But we know that it is light some time after the sun has set and before he rises in the morning, and call these appearances *twilight* and *dawn*. (Fig. 5.) It is found that

this illumination lasts as long as the sun is less than eighteen degrees below the horizon. The sun takes nearly two months to sink through this amount at the poles, and two months afterwards he is again only 18° below the horizon. In latitude 50°, twilight lasts nearly two hours in March and October, nearly four hours at the end of May, and as the sun does not get eighteen degrees

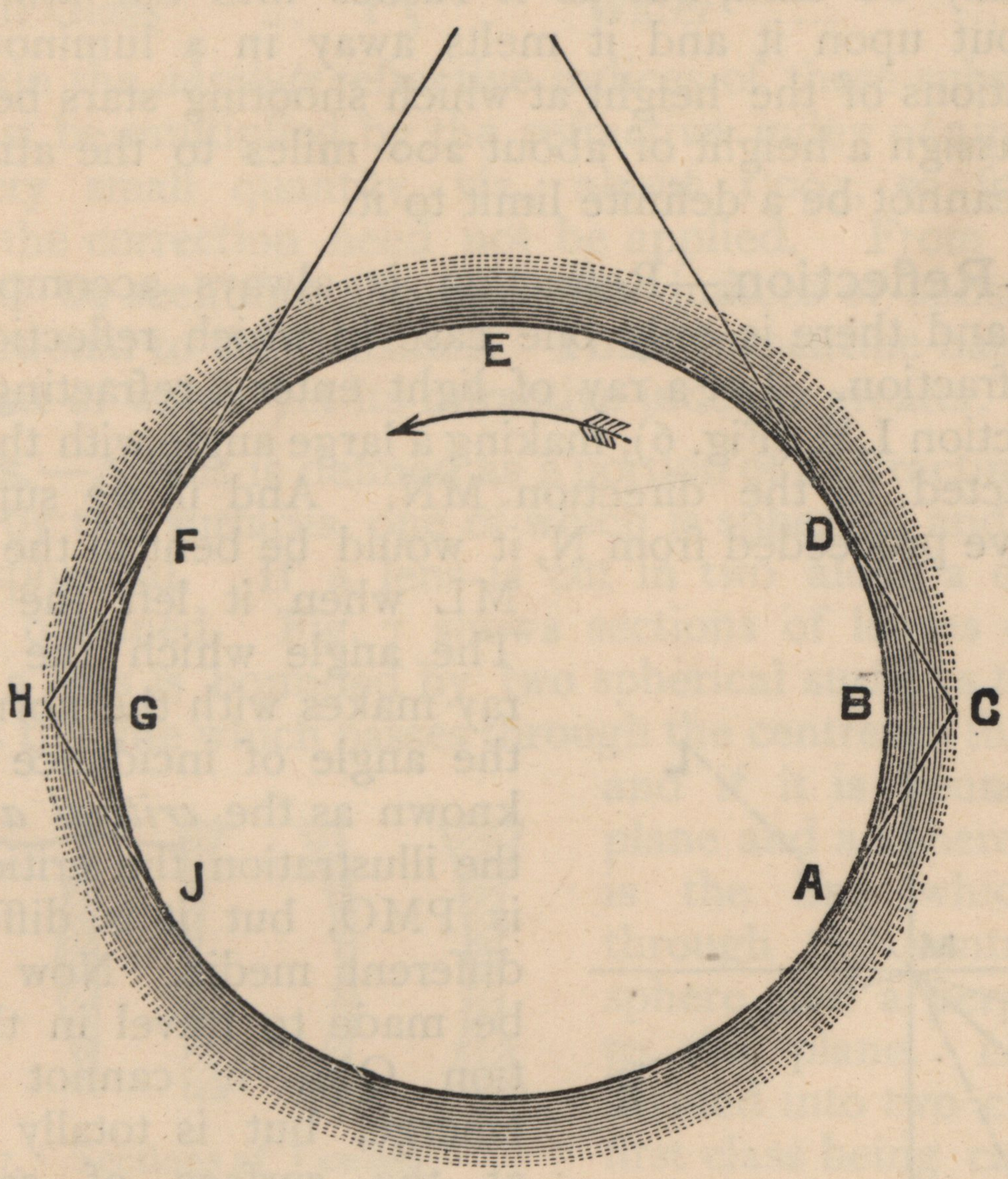


Fig. 5. Dawn and Twilight. An observer at A is in darkness, at B he receives the diffused light of the sun shining upon the atmosphere at C, at D, E, and F he receives the direct rays of the sun. Similarly, at G twilight occurs until J is reached and no part of the atmosphere is visible upon which the sun is shining.

below the horizon during June, in this month it is light all night. This phenomenon is caused by the reflection and scattering of the light of the sun by clouds and particles in the upper regions of the earth's atmosphere. Its duration therefore depends upon the height of the atmosphere and the angle at which the sun's rays cut it. At the equator the sun's rays cut through the atmosphere at the shortest path. In higher latitudes, however, they strike it

obliquely, hence the duration of twilight is greater. From the phenomena of dawn and twilight astronomers find that the atmosphere extends about 45 miles, but luminous meteors and shooting stars afford a means of proving that it exists much higher in a very rarefied form. A shooting star or meteor is a particle of matter drawn into the earth from outer space. In space it may be dark, but as it rushes into our atmosphere a brake is put upon it and it melts away in a luminous streak. Determinations of the height at which shooting stars begin to be luminous assign a height of about 200 miles to the atmosphere, but there cannot be a definite limit to it.

Total Reflection.—Refraction is always accompanied by reflection, and there is only one case in which reflection occurs without refraction. Let a ray of light enter a refracting medium in the direction LM (Fig. 6), making a large angle with the normal. It is refracted to the direction MN. And if we suppose the light to have proceeded from N, it would be bent in the direction ML when it left the medium. The angle which the refracted ray makes with the normal when the angle of incidence is 90° is known as the *critical angle*. In the illustration the critical angle is PMO, but it is different for different media. Now if a ray be made to travel in the direction QM, it cannot possibly emerge, but is totally reflected at the surface of separation, and takes up the direction MR. All rays, then, having angles of incidence greater than the critical angles, when passing from the more refractive medium, undergo total internal reflection. The phenomenon can be seen by putting an empty bottle into a glass of water. The light that enters the water strikes against the side of the bottle and is reflected, making the bottle appear as though it had been silvered.

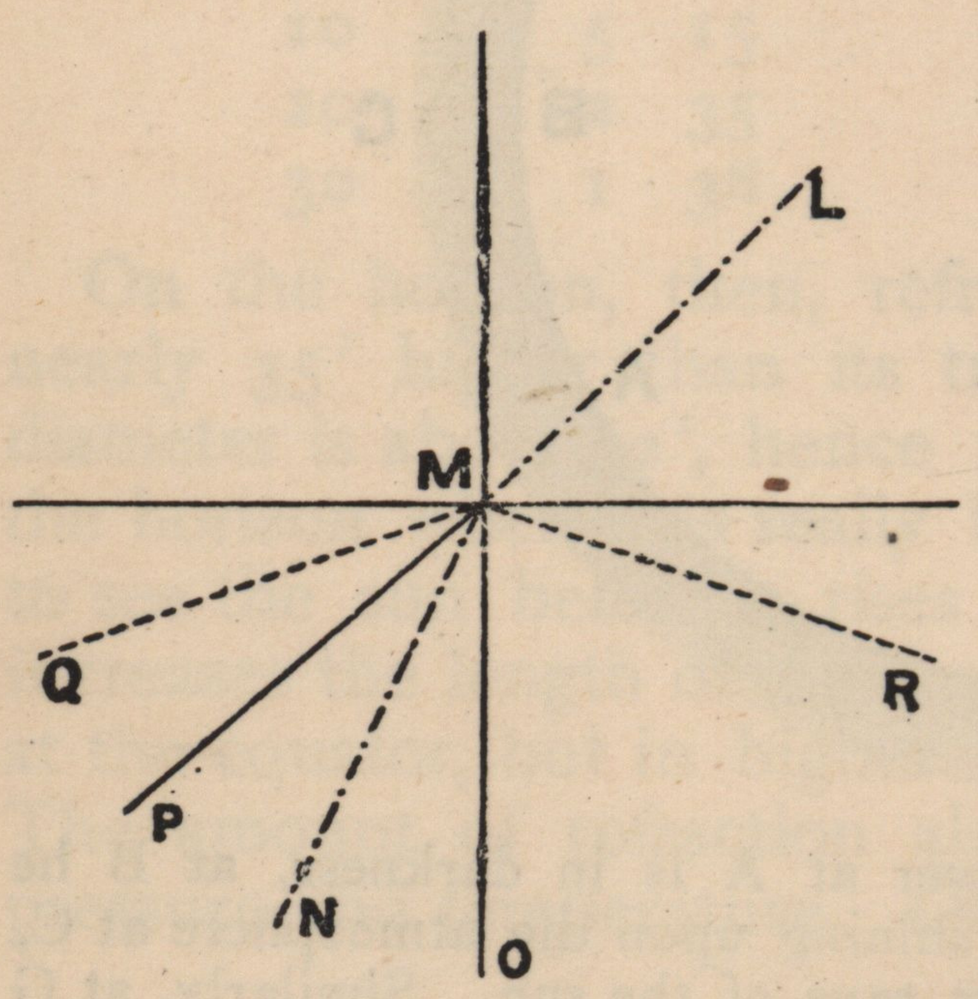


Fig. 6. Illustrating total reflection in a refractive medium.

Refractive Indices.—We have said that the ratio which the sine of the angle of incidence bears to the sine of the angle of

refraction is constant for any two media. It can therefore be expressed numerically. The following values have been obtained when the light passed from air into the media :—

Diamond	2·4	Carbon bisulphide	1·6
Ruby	1·7	Turpentine ...	1·5
Flint Glass ...	1·6	Chloroform ...	1·4
Crown Glass ...	1·5	Water	1·3

To obtain the *absolute* refractive indices of these substances the values must be multiplied by the refractive index of air. This is only a very small quantity, viz., about 1·003, so for general purposes the correction need not be applied. From the above table it will be seen that the refractive indices of substances are not proportional to the densities. Thus, turpentine has a density about $\frac{4}{5}$ that of water, yet its refractive index is greater.

Lenses.—A lens is defined as a portion of a refracting medium bounded by two surfaces, one of which is spherical and the other plane or spherical. If a lens is cut in two along a diameter a section is obtained. Fig. 7 shows sections of lenses commonly used. If a lens is bounded by two spherical surfaces the axis of the lens is the line which passes through the centres of the spheres ; and if it is bounded by a plane and a sphere, the axis is the line which passes through the centre of the sphere and a perpendicular to the plane. Lenses are divided into two classes, the first class being called positive or concave lenses, and the second negative or convex. Convex lenses are thicker in the middle than at the edges, while the reverse is the case for concave lenses. The ray of light which travels through a lens along the axis and those which pass through the centre of the lens suffer no deviation. All other rays are bent towards the thicker part of the lens. In the case of a convex lens, therefore, these rays are bent or *converged* towards the axis, and eventually cross each other. On the other hand, a concave lens has a *divergent* action upon the rays, sending them away from the axis. But these actions are only true for lenses denser than the medium surrounding them. For if the medium enclosed by a lens is less dense than that surrounding it, the opposite effects are produced, that is to say, a concave



Fig. 7. Sections of Lenses.

lens becomes a converging lens, while a convex one is divergent.

Formation of Real Images by Lenses.—If a candle is placed on one side of a convex lens and at a distance from the lens greater than that of the principal focus, an inverted image can be caught upon a screen at the other side of the lens. On moving the candle away from the lens the image advances towards the lens and becomes smaller. Fig. 8 illustrates the course of rays

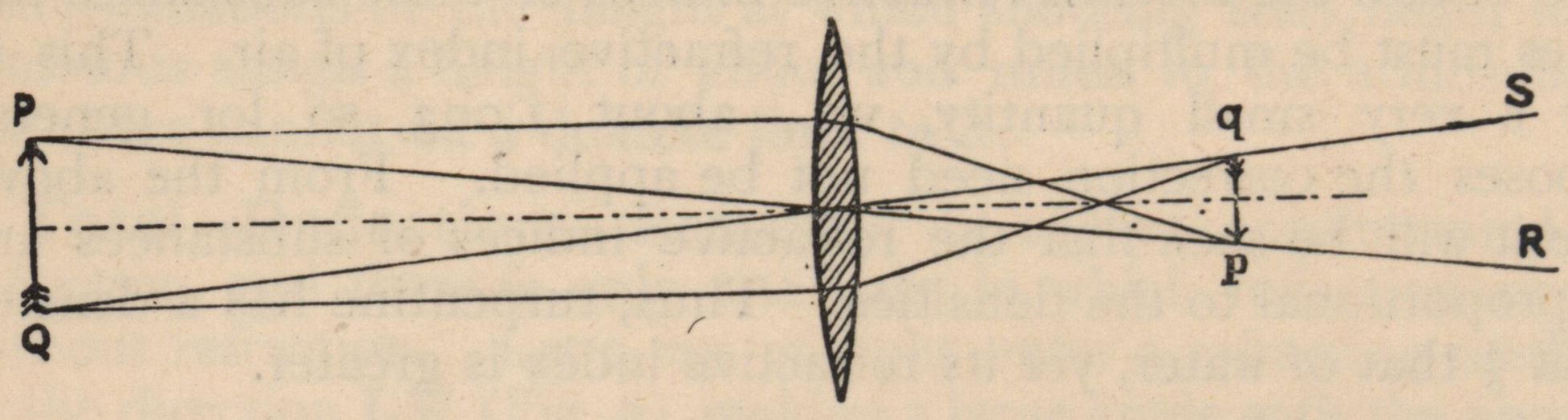


Fig. 8. Course of rays forming an inverted and reduced image of an object.

which form this image. Let PQ represent the candle. We require to determine the position of its image. A straight line drawn from P to the centre of the lens suffers no deviation so it can be continued on the other side. A similar secondary axis can

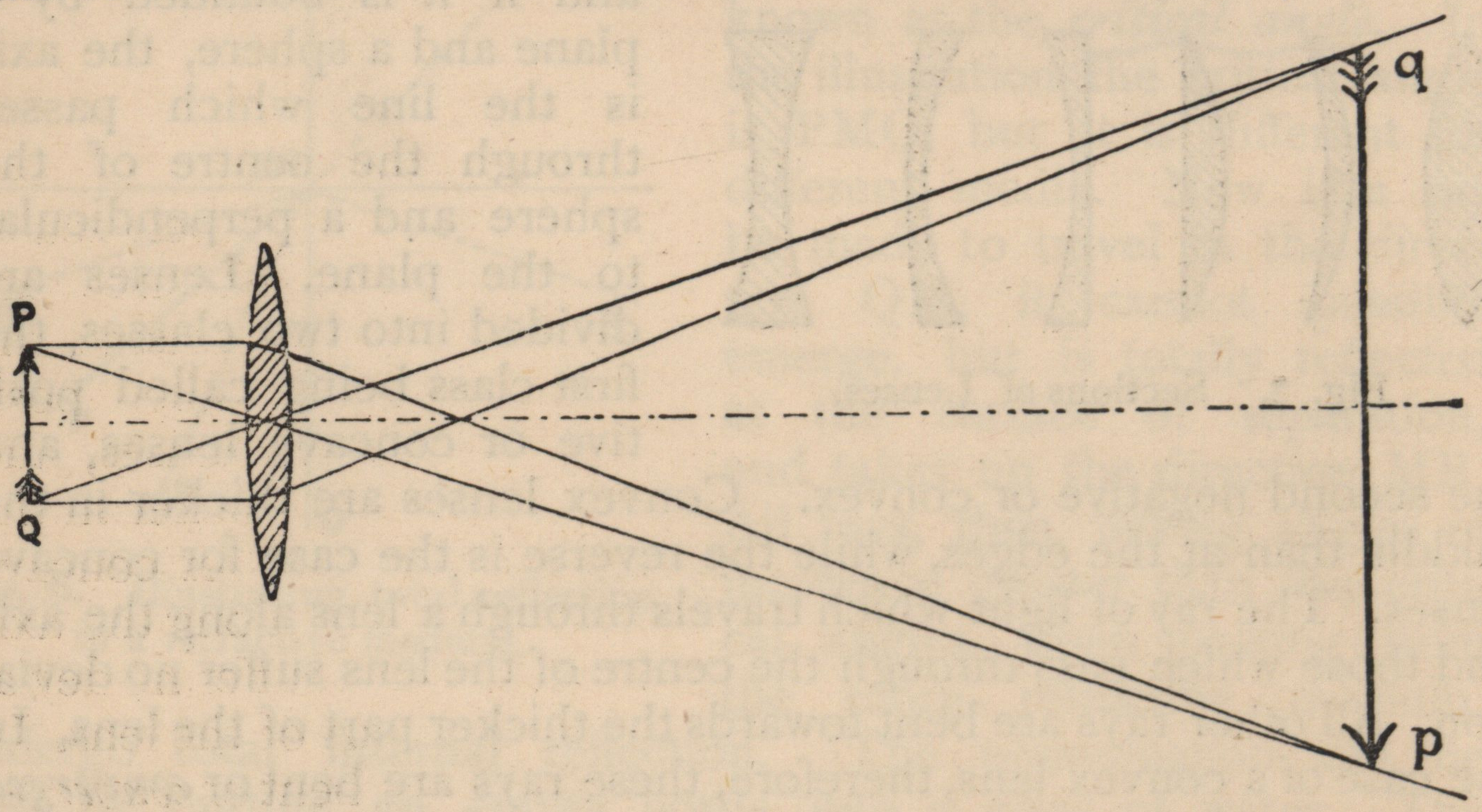


Fig. 9. Course of rays whereby a lens forms a magnified image of an object.

be drawn from Q. The image of the point P must therefore be found on the line PR, and the image of Q must be above it on the line QS. Draw lines parallel to the principal axis from P and Q.

These rays will be refracted to the principal focus, and if continued through the focus will meet the secondary axis. The points of intersection locate the images of P and Q at pq. If the candle is at a distance less than twice the focal length of the lens, a magnified inverted image is seen instead of a diminished one. The course of the rays in such a case is shown in Fig. 9.

Relations between Image and Object.—If a candle and its image are at the same distances from a lens, the length of each is the same. In fact, there is a definite relation between the linear dimensions of the two, and it is expressed by the following proportion :—

$$\text{Distance of image from the lens} : \text{Distance of object from the lens} :: \text{Length of image} : \text{Length of object}$$

If PQ represent the length of an object, pq the length of its image, p the distance of the object from the lens, and f the focal length of the lens, it can be shown that

$$\frac{PQ}{pq} = \frac{f}{p-f}$$

Suppose PQ = 2 inches, f = 6 inches and ρ = 18 inches,

$$\text{Then } pq = \frac{PQ\ (p-f)}{f}$$

$$= \frac{2\ (18-6)}{6}$$

$$= 4 \text{ inches.}$$

It is not essential to use a beam of parallel rays for determining the focal length of a lens, for if p represent the distance of an object from the lens, p' the distance of lens from the image, and f the focal length,

$$\frac{1}{p'} - \frac{1}{p} = \frac{1}{f}$$

Distances measured on the same side as the incident light are considered to be positive, and distances measured on the opposite side are called negative.

If the radii (r and s) of the surfaces of the lens and the refractive index (μ) are known, the focal length can be found from the following formula :—

$$\frac{1}{f} = (\mu - 1)\ \left(\frac{1}{r} - \frac{1}{s}\right)$$

Virtual Images.—When an object is at a less distance from a lens than the focal length, no real image is produced; but if the eye is used to view the object through the lens under such cir-

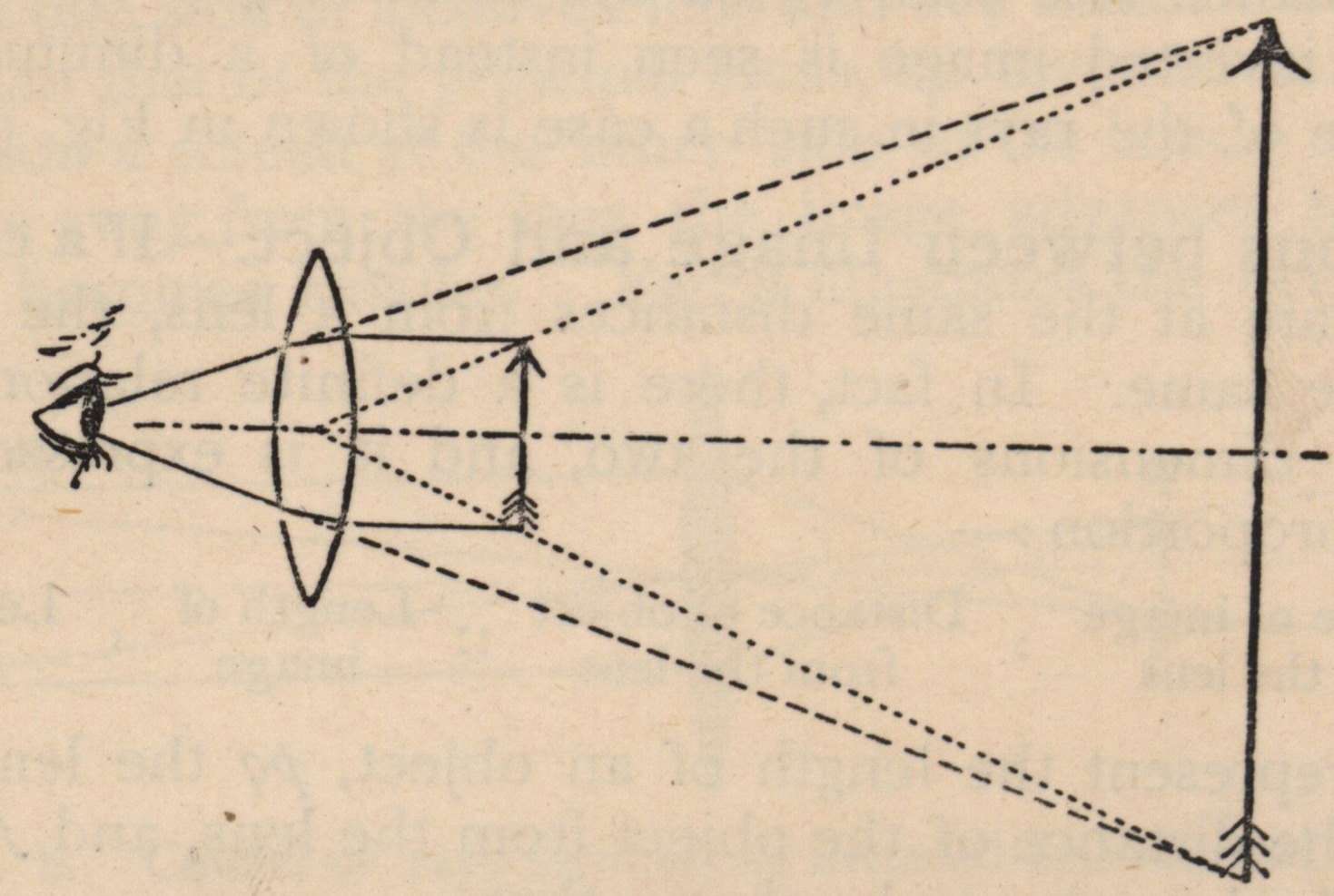


Fig. 10. Magnification by means of a convex lens of short focal length.

cumstances, an erect magnified image will be seen. This property is utilised in an ordinary magnifying glass, and the course of rays which construct the image is shown in Fig. 10.

The Photographic Camera.—The optical principles underlying the construction of the camera used by photographers will now be easily followed. A lens, which for simplicity we will consider as a simple convex one, is fixed in the centre of one of the sides of a dark box. The side of the box behind the lens consists of a plate of ground glass capable of being moved to or from the lens. If the camera is now directed to any object, a diminished and inverted image of the object is seen upon the ground glass, and, by adjustment, this can be brought into proper focus. A plate sensitive to light rays is then put in the place of the ground glass, and exposed in such a manner that only the light which comes through the lens can act upon it. The sensitive plate thus receives the impressions, and by treating it with proper chemicals the picture is rendered permanent.

The Eye.—A great similarity exists between the structure of the eye and a photographic camera. Both consist essentially of a lens to form an image and a sensitive screen behind to receive it. Fig. 11 is a section of an eye, showing the most important parts. The white of the eye, or the sclerotic coat, is a hard opaque layer, having for its function the protection of the eye

A portion of the sclerotic coat is transparent and is called the cornea. Behind this occurs the iris, which consists of a diaphragm having a hole in it to form the pupil. The iris possesses the important property of contracting when the light is very bright, and opening when the light is faint. At the back of the cornea is the crystalline lens, which is analogous to the lens of a camera. Between the two parts is found a liquid material known as aqueous

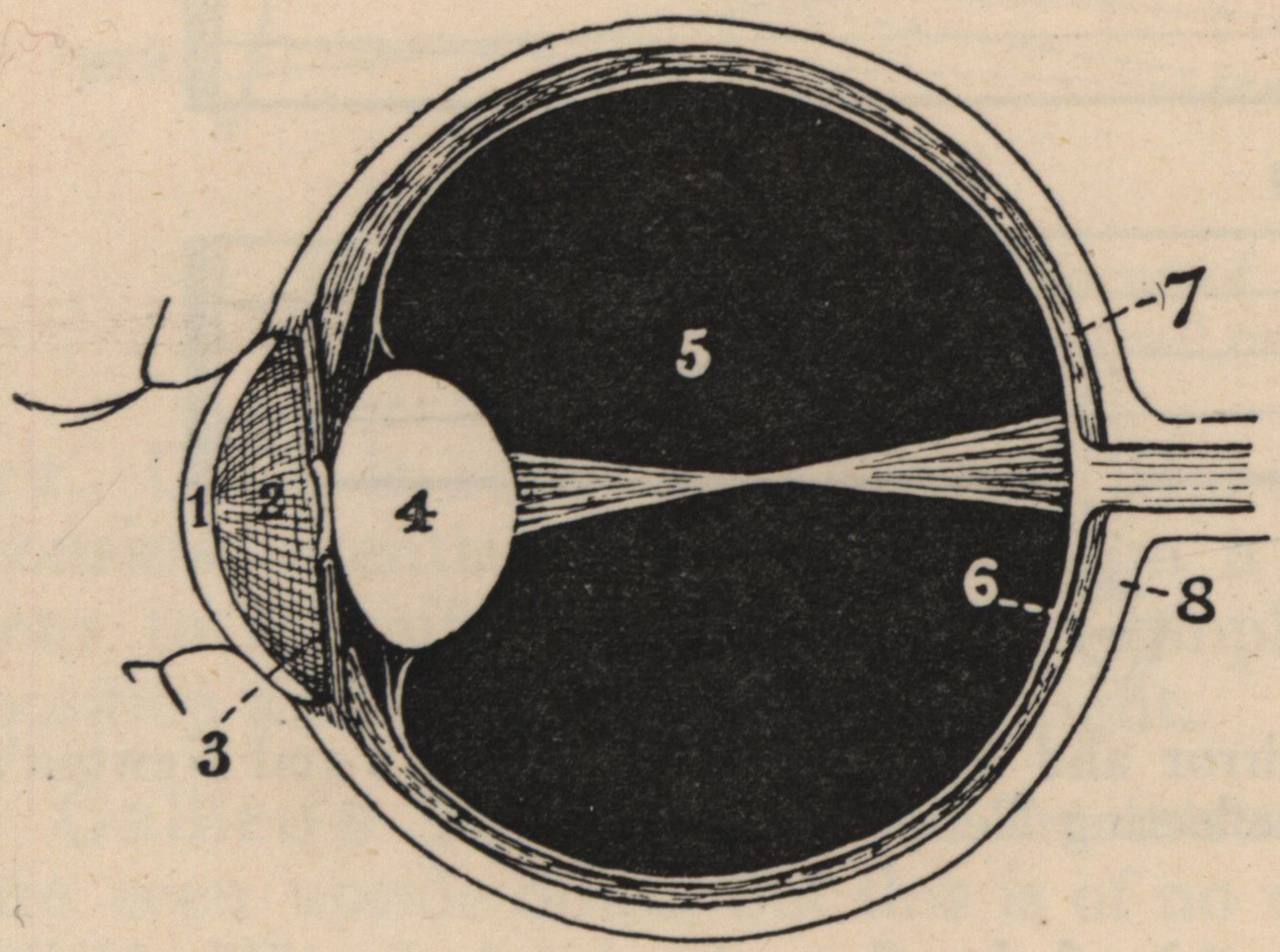


Fig. 11.

1. The Cornea.
2. Aqueous Humour.
3. Iris.
4. Crystalline Lens.
5. Vitreous Humour.
6. The Retina.
7. Choroid Coat.
8. Sclerotic Coat.

humour, while a more gelatinous substance, termed vitreous humour, fills the space between the crystalline lens, and the back of the eye. The choroid coat beneath the sclerotic coat contains a black substance which prevents internal reflection. Beneath it is found the retina, which is composed of a network of fibres in connection with the optic nerve. The retina is analogous to the sensitive plate of the photographer. Directly in the centre of the retina a slight depression occurs, and it is found that the sense of sight is keenest at this point.

The distance at which an object is clearly seen by the average eye is ten inches. A simple microscope or magnifying glass enables us to view the object much nearer than this, and we see it correspondingly enlarged.

Reflecting Telescopes.—There are several kinds of reflecting telescopes in which a parabolic or a concave mirror takes the place of the object glass of the more common kind of instrument. The same eye-piece can be employed with a reflector or a refractor. In the Herschellian reflector—so called because it was invented by Herschel—the curved mirror is fixed slantingly

in the bottom of the telescope tube. Rays from an object pass down the tube and the image is reflected to the eye-piece L. (Fig. 12.) The curved mirror is fixed squarely in the bottom of the tube in the case of the reflector invented by Newton and termed the Newtonian telescope. Near the top of the tube a plane mirror is fixed at an angle of 45° to the axis. The image formed

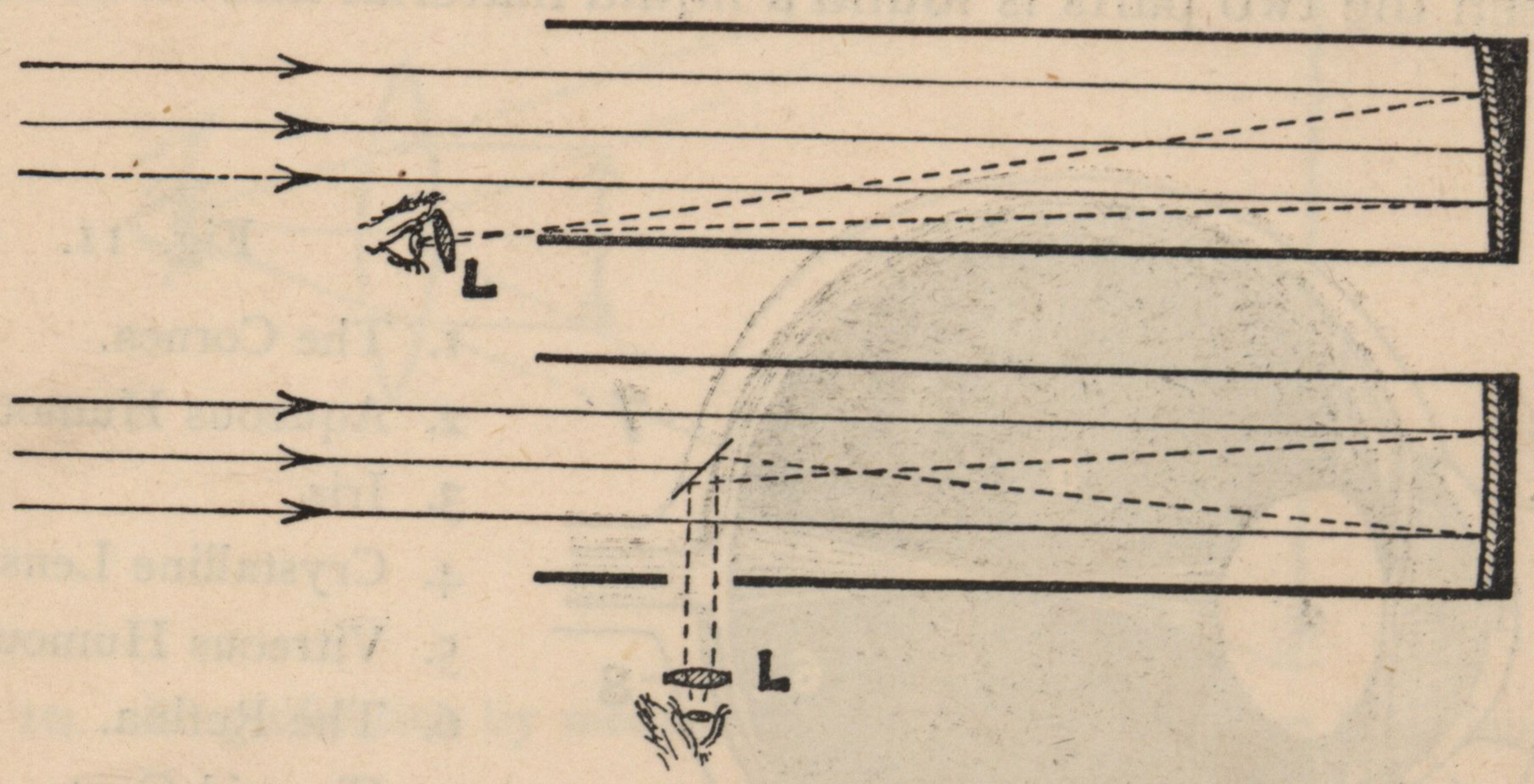


Fig. 12. Arrangement of Mirror and Eye-piece in Herschel's and Newton's Reflecting Telescopes.

by the curved mirror is received by the plane mirror, technically known as the 'flat,' and thence reflected to the eye-piece L fixed in the side of the tube. The flat stops a few of the rays from the object under observation and a certain amount of light is lost by the second reflection, nevertheless, the Newtonian form of reflector is more commonly used than any other.

Spherical Aberration.—The inability of a spherical mirror to bring all parallel rays to one focus obtains also to lenses, and is known as spherical aberration. Only those rays which pass through a lens near the principal axis are brought to one focus; rays near the edge of the lens have their foci at other points. To obviate this defect, photographers insert a diaphragm near one of the faces of the lens in their camera, and this only permits light to pass through the central portion of the lens. The smaller the hole in the diaphragm, the more distinct is the picture obtained, with the disadvantage, however, that its brightness is diminished.

Course of Rays in a Telescope.—An object, PQ, not shown in Fig. 13, is at a great distance from the centre C of the large lens or object glass. Rays from it pass through

the object glass and produce an inverted image, *qp*. A smaller convex lens, known as the eye lens, is placed so that the real image, *pq*, is at a shorter distance from it than its principal focus. The result is that an inverted, magnified, virtual image of PQ,

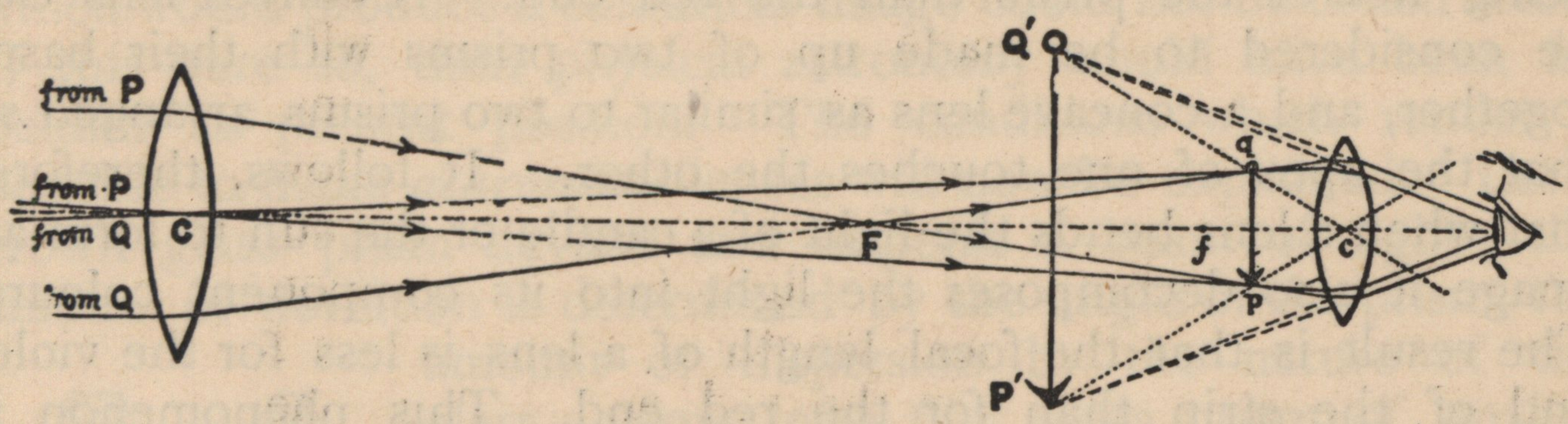


Fig. 13. F is the principal focus of the large lens and *f* that of the small one.

viz., Q'P', is seen by the eye. Hence the simple telescope consists essentially of a lens to form a real image and another lens to magnify it. The tube is simply to keep the lenses in position and shut out extraneous light.

Galileo's Telescope.—In the astronomical telescope objects are seen upside down, but this is of no consequence for celestial work. The first telescope showed objects in their true position. This was the kind of instrument used by Galileo, and the lenses in it are similar to those in a common opera-glass or toy telescope.

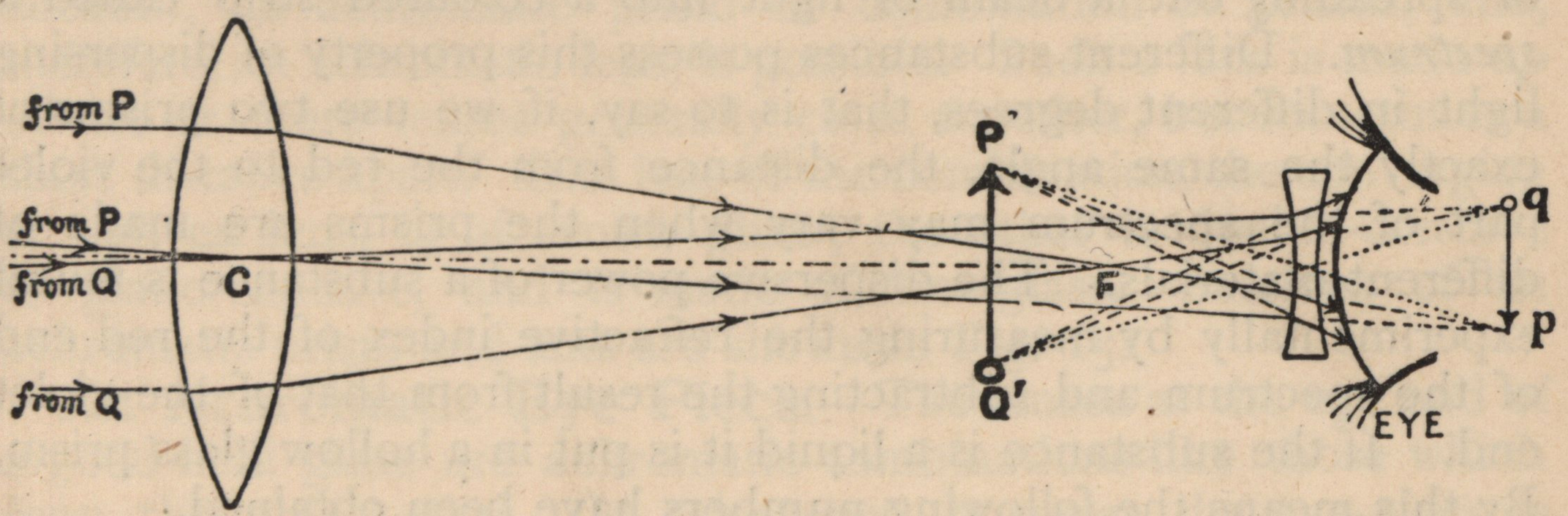


Fig. 14. Course of rays in Galileo's Telescope.

The course of rays whereby the image of an object is obtained is shown in Fig. 14. A distant object, PQ, has its image, *qp*, formed by means of the large lens with the centre C. A small concave lens intercepts these rays short of the image and bends them to the eye so that they appear to come from P'Q', which is an erect, virtual, and magnified image of PQ.

Refraction and Dispersion. — In 'Elementary Physiography' it is shown that when a beam of sunlight passes through a prism it is bent out of its original direction and broken up into the colours of the rainbow, the violet end of the coloured strip being nearer the prism than the red end. A convex lens can be considered to be made up of two prisms with their bases together, and a concave lens as similar to two prisms arranged so *that the apex of one touches the other. It follows, therefore, that when a lens bends the light of a candle or the sun to form an image it also decomposes the light into its component colours.* The result is that the focal length of a lens is less for the violet end of the strip than for the red end. This phenomenon is known as chromatic aberration. In fact, the amount by which a beam of light is refracted depends upon the quality of the light. Hence, tables of refractive indices, to be accurate, generally state the kind of light for which the values given are true. Three causes, then, determine the amount of bending; they are—(1) the angle of the prism or lens; if the opposite sides are nearly parallel to one another there is little bending; as the angle is increased the difference between the original and refracted directions is also increased; (2) the nature of the refracting medium; (3) the quality of light employed, red light being least refracted while violet light is the most refracted colour.

So much for the refractive power. Now as to the capability of spreading out a beam of light into a coloured strip called a *spectrum*. Different substances possess this property of dispersing light in different degrees, that is to say, if we use two prisms of exactly the same angle, the distance from the red to the violet part of the spectrum may vary when the prisms are made of different materials. The dispersive power of a substance is found experimentally by measuring the refractive index of the red end of the spectrum and subtracting the result from that of the violet end. If the substance is a liquid it is put in a hollow glass prism. By this means the following numbers have been obtained.

Substance.	Dispersive Power.
Flint Glass	0·052
Crown Glass ...	0·033
Turpentine	0·023
Water	0·013

An Achromatic Lens.—Newton found that if a beam of light which had passed through a prism were sent through

another prism of the same kind, the latter entirely neutralised the effect of the former, both as regards refraction and dispersion. His experiments led him to the conclusion that it was impossible to bend a beam of light without dispersing it ; that, in fact, a lens which would produce a colourless image could not be constructed. If this were so, then physical astronomy would have been far behind its present position. The conditions which render it possible to make *achromatic* lenses will now be explained. Let a crown glass prism deviate and disperse a beam of light; the amount of deviation is determined by the angle of the prism, the amount of dispersion by the nature of the glass. Now, let a flint glass prism of smaller angle be placed so that the edges of the two are in opposite directions. This prism will almost undo the deviating effect of the other, and since the dispersive power of flint glass is greater than that of crown glass, it is possible to neutralise entirely the dispersive effect of the crown glass prism by means of a flint glass prism of smaller angle and still retain some deviation. The effect of the crown glass thus predominates as far as deviation goes, owing to the larger angle, while the flint glass predominates with respect to dispersion. On this account, an achromatic prism or combination of prisms, and, therefore, an achromatic lens, is possible. Such a lens is made up of two or more lenses generally close together, but sometimes a short distance apart. One lens of the combination, the converging or convex lens, is of crown glass; the other is double-concave or plano-concave, and is made of flint glass. Sections of an achromatic prism and lens are shown in Fig. 15.

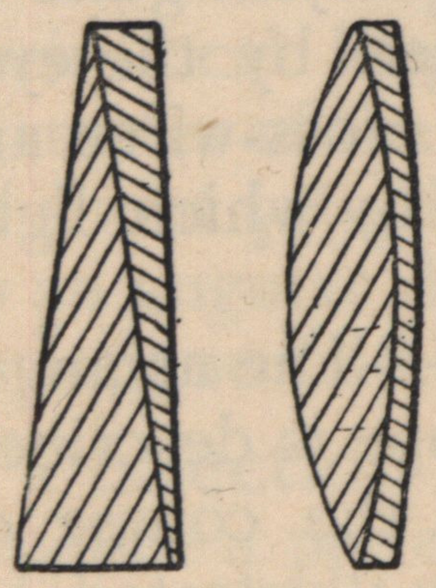


Fig. 15.

Sections of an Achromatic prism and an Achromatic lens.

An Achromatic Eye Piece.—The lenses at the eye end of a good field glass are achromatic combinations like those which form the object-glass. In telescopes, however, the eye-piece is usually made up of a couple of convex lenses fixed a short distance apart. A Huyghens, or *negative*, eye-piece is obtained by arranging two lenses at a distance from each other equal to half the sum of their focal lengths. Between the two a diaphragm is generally fixed. The Ramsden, or *positive*, eye-piece is often used instead of the negative one. Unlike the latter, its focus lies outside the combination, so it can be used as a magnifier in the same way as a simple convex lens. In each of the combinations the

lens nearer the object-glass is known as the field lens, while the other goes by the name of the eye lens. When the astronomical telescope has to be accurately directed towards a particular star, it is useful to have a means by which a point in the field of view is indicated. This desideratum is obtained by means of a couple of spider lines or fine threads intersecting in the field. In the negative eye-piece the lines are stretched across the hole in the diaphragm and so furnish a fixed reference mark; in the positive eye-piece they are stretched across each other slightly in front of the combination. The cross-wires, as these spider lines are generally termed, must lie in the focus of the object-glass of the telescope, so that when the image is magnified by the eye-piece the wires are magnified also. When the cross-wires are very fine they are very difficult to see. A means by which light can be reflected to them is therefore necessary.

An Achromatic Astronomical Telescope.—The arrangement of lenses and tubes in an astronomical telescope is described and figured in 'Elementary Physiography,' and the course of rays by which an image of an object is produced is illustrated by preceding figures. It is now necessary to state in what way the telescope helps our vision. The brightness of the image of a star seen by means of a telescope increases as the size of the object-glass is increased. Roughly speaking, the illuminating powers of telescopes are proportional to the areas of their object glasses. The only reason that large lenses are made is that more light shall be collected. And since the area of a circle varies as the square of the diameter, the illuminating power of the telescope varies as the square of the diameter of the object-glass exposed to the sky. But this is not strictly true. As object-glasses increase in size they also increase in thickness, and therefore absorb more light. Neither does the rule hold good in the case of the sun or moon, or any object presenting a real disc, for then the light is not concentrated to a point but spread over an appreciable area and is accordingly diminished in intensity, though, of course, the object appears much brighter than when seen with the unaided eye.

The magnifying power of a telescope, or, indeed, of any combination of lenses, is equal to the focal length of the object-glass divided by that of the eye-piece. The focal length of the former is constant, hence, to vary the magnification, the eye-piece must be varied. For astronomical purposes, magnifying powers from 100 to 500, that is, eye-pieces magnifying from 100 to 500 diameters, are commonly used.

Spurious Discs.—A planet or any member of our solar system can be magnified in the telescope ; they appear as discs of light. The stars are so far away that they cannot be magnified, though they also show more or less distinct discs, known as *spurious* discs to distinguish them from the *real* discs. It can be proved that, since light consists of waves, the image of a luminous point must appear as a small disc surrounded by concentric rings which diminish in intensity away from the centre. The diameter of the spurious disc varies in inverse proportion to the diameter of the object glass. The larger the glass the smaller the disc. It has been experimentally found that 'In all objectives having their focal lengths equal to 15 times the aperture, the linear diameter of the spurious disc may be said to average 0·0004 inch, or about $\frac{1}{2500}$ inch. With six inches aperture, this corresponds to an angular diameter of 0·9 second, and in a 12-inch aperture to 0·45 second.'

Perfection of Image.—When everything has been done to produce a perfect telescope the result is rarely satisfactory, for there are so many disturbing causes. It has been said that the conditions to be satisfied before perfection is attained are as follows :—

(1.) The optic axis of the flint and crown glass lenses should be coincident.

(2.) This common axis should pass through the centre of the eye-piece.

(3.) The dispersions of the flint and crown should neutralise each other for the most visible rays of the spectrum.

(4.) There should be no spherical or zonal aberration.

(5.) The lenses should have surfaces which are truly parts of spheres. (*Nature*, December 31st, 1891.)

And we may add to this that the capabilities of a telescope depend upon the eyes of the observer.

QUESTIONS ON CHAPTER I.

1. Describe the construction of the achromatic object-glass. (May, 1884.)

2. Explain the meaning of the following terms :—Refraction, dispersion, achromatic object-glass.

3. What is the theory now accepted as to the nature of light, and what crucial experiment established it ?

4. If the sun were placed at ten times its present distance from the earth, to what extent would its light be affected?

5. A particular star appears 100 times brighter than another near it. Assuming that both are of the same size and possess the same intrinsic luminosity, what is the difference between their distances from the earth?

6. Describe a method by means of which the velocity of light has been determined on the earth.

7. What is meant by the 'albedo' of a planet? Explain fully.

8. Enumerate the laws of refraction of light.

9. What effect has atmospheric refraction upon the place of a star?

10. Describe the chief effects of refraction in the earth's atmosphere upon celestial objects.

11. What is a lens? Draw the course of rays in a simple astronomical telescope.

12. Explain the meaning of the term 'refractive-index.'

CHAPTER II.

ASTRONOMICAL INSTRUMENTS AND THEIR USE.

THE optical principles which underlie the construction of the telescope have already been described. But, however perfect a telescope may be, it is of little use unless mounted on a proper stand, and the different kinds of mountings usually adopted will be dealt with in this chapter. During the last thirty years the photographic camera and the spectroscope have been added to the telescope and considerably extended the range of research. These also will be described, but the results obtained with them are reserved for a future chapter.

Before the invention of the telescope in 1610, the work of astronomers was confined to observing the positions and motions of the heavenly bodies; after it became possible to investigate the nature of the bodies themselves. In fact, astronomical telescopes fall into two great classes, one having for its object the accurate determination of celestial co-ordinates, and so developing the astronomy of the ancients, the other investigating the physics and

chemistry of the bodies in the sky. To understand the work of the former class, it is necessary to explain the celestial co-ordinates which are determined by instruments belonging to it.

For the purpose of measurement, the heavenly bodies are supposed to be projected upon a sphere having the earth at its centre and extending to an infinite distance on all sides. This is the celestial sphere. In order to locate a point upon it, some reference mark must be adopted from which positions are counted. If any great circle is selected, then all great circles which cut it perpendicularly pass through its poles. The former, which is analagous to the earth's equator, is termed the primary circle, and the latter, which are similar to meridians of longitude, are secondaries to it. In 'Elementary Physiography,' three planes are defined: (1) the plane of the horizon, (2) the plane of the earth's equator, (3) the plane of the ecliptic. Each of these planes, when produced, meet the celestial sphere, and the great circles thus formed upon it giverise to different systems of celestial co-ordinates. We will describe these systems in order.

Altitude and Azimuth System of Co-ordinates.—The *visible* horizon is the line where earth and sky appear to meet. By projecting the plane of the horizon upon the celestial sphere, a circle is produced of which the eye of the observer occupies the centre; this is the *sensible* horizon. The *rational* horizon is a great circle parallel to the sensible horizon, but passing through the centre of the earth instead of the eye of the observer. The cardinal points, North, South, East, and West, furnish marks from which positions along the horizon are reckoned. The line passing through the eye of the observer perpendicular to the horizon is the *vertical*. Its direction is the same as that of a plumb line. This line produced upwards meets the visible hemisphere at a point directly overhead, called the *zenith*, while the opposite point in the celestial sphere, where the vertical line meets the sky, marks the *nadir*. This is the point directly under foot. All secondary circles must pass through both the zenith and the nadir, and are termed *vertical circles*. The *celestial meridian* is the vertical circle which passes through the north and south points of the horizon. When an object appears on the meridian of an observer it is said to transit or culminate. The *prime vertical* is the vertical circle at right angles to the celestial meridian, that is, which passes through the east and west points. *Altitude* signifies angular distance above the horizon, measured on a vertical circle; its complement is angular distance from the zenith, that is, *zenith*

distance. *Azimuth* is angular distance from the north or south points, measured along the horizon; more accurately, it is the arc of the horizon between the foot of a vertical circle and the north or south points; its complement is *amplitude*, that is, angular distance from the east or west points. In astronomy it is usual to start from the southern point and count azimuths through the west point completely round the horizon, the angles thus ranging from 0° to 360°. Navigators count from the north or south points up to 180°. Some surveyors count from the north point towards the right hand up to 360°, others express their azimuths in the same way as navigators.

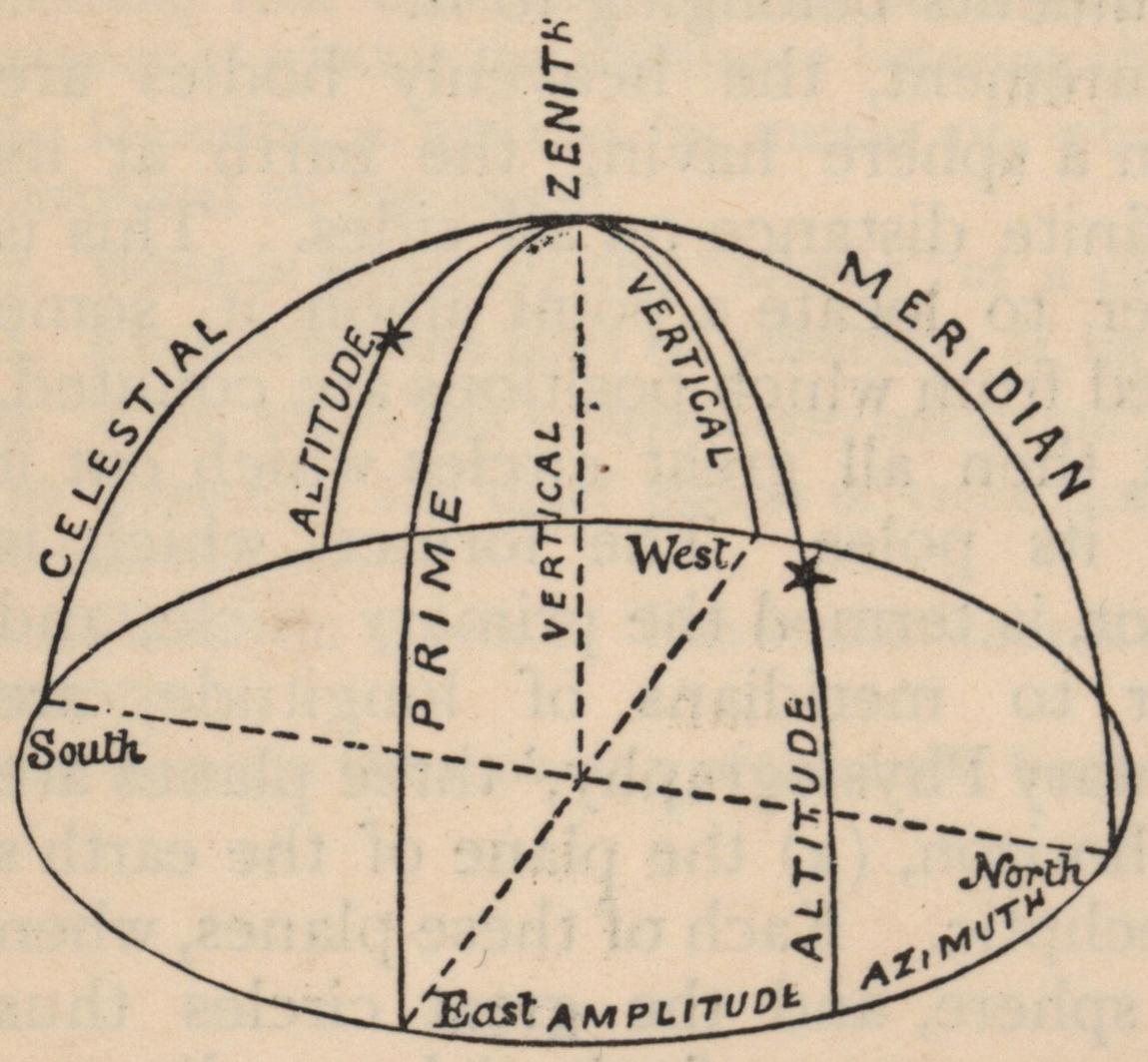


Fig. 16. Altitude and Azimuth System of Co-ordinates.

All these terms are illustrated by Fig. 16.

Theodolites and Alt-Azimuth Instruments.—The theodolite is the instrument used in surveying. (Fig. 17.) It consists essentially of a telescope capable of moving in a vertical plane, and supported on pillars resting on a base, which can be rotated in a horizontal plane. To determine altitudes and azimuths with this instrument, it is necessary (1) that the base should be perfectly horizontal, (2) that the motion of the telescope should be in a vertical circle. To realise the first desideratum the instrument is supported on three screws adjustable in height, and two spirit levels, at right angles to one another, are attached to the base. The levelling screws are adjusted until the air bubble in each of the spirit levels is at the centre of the tube in which it moves. The base is then perfectly level, and no disturbance of level should take place when the pillars are turned completely round. On looking through the telescope two fine wires crossing one another will be seen. The point where these wires intersect is fixed, and so serves as a convenient mark of reference in the field of view of the telescope. To determine the horizontal angle between any two objects, the telescope is first directed to one of them, the cross-wires made to bisect it, and the reading of the angle on the

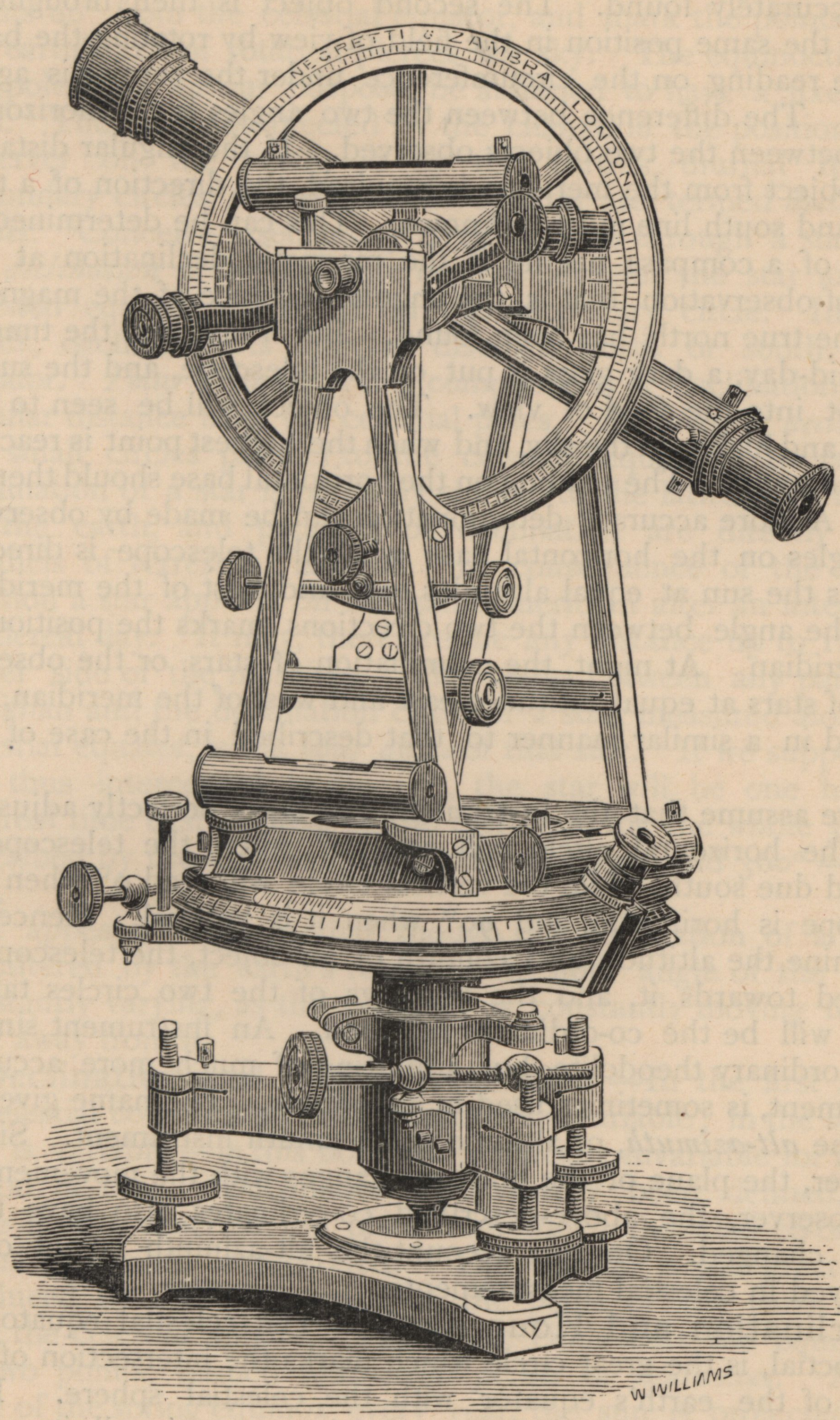


Fig. 17. Instrument for determining Altitude and Azimuth.

horizontal base noted. The fixed vernier enables this angle to be very accurately found. The second object is then brought to exactly the same position in the field of view by rotating the base, and the reading on the circumference under the vernier is again taken. The difference between the two angles is the horizontal angle between the two objects observed. If the angular distance of an object from the meridian is required, the direction of a true north and south line must be known. This can be determined by means of a compass needle if the magnetic declination at the place of observation, that is, the angular distance of the magnetic from the true north, has been found. But if not, and the time is near mid-day, a dark glass is put on the telescope, and the sun is brought into the field of view. The object will be seen to get higher and higher in the sky, and when the highest point is reached it is due south. The reading on the horizontal base should then be zero. A more accurate determination can be made by observing the angles on the horizontal base when the telescope is directed towards the sun at equal altitudes east and west of the meridian. Half the angle between the two directions marks the position of the meridian. At night, the culmination of stars, or the observations of stars at equal altitudes east and west of the meridian, can be used in a similar manner to that described in the case of the sun.

If we assume that the instrument has been perfectly adjusted, then the horizontal circle will read 0° when the telescope is pointed due south, while the vertical circle will read 0° when the telescope is horizontal, and 90° when it is vertical. Hence, to determine the altitude and azimuth of an object, the telescope is directed towards it, and the readings of the two circles taken. These will be the co-ordinates required. An instrument similar to an ordinary theodolite, but admitting of much more accurate adjustment, is sometimes used in astronomy. The name given to it is the *alt-azimuth*, or altitude and azimuth instrument. Since, however, the plane of the horizon changes with the movement of the observer, the above-described co-ordinates also have their values changed. On this account the alt-azimuth is not often employed in celestial measurements.

Declination and Hour Angle.—The celestial equator, or equinoctial, is the great circle which marks the intersection of the plane of the earth's equator with the celestial sphere. It is therefore directly above the terrestrial equator in all its parts. This is the primary circle which gives rise to the system of

co-ordinates now to be described. The celestial poles are the points 90° from the celestial equator, and mark the points where the earth's axis of rotation pierces the sky. The equinoctial and the poles can, for our purpose, be assumed to have a fixed position. They are not affected by the change in the position of an observer on the earth, or by the earth's diurnal rotation. Secondary circles to the celestial equator are termed *declination circles*. Conceive a secondary circle to pass through a star, then the *declination* is the arc intercepted between the star and the celestial equator, measured on the secondary circle. In other words, declination is angular distance north or south of the equator. *Polar distance* is the complement of declination, being angular distance from the celestial poles. *Parallels of declination* are small circles parallel to the celestial equator. In fact, the declination of a star is precisely similar to the latitude of a place on the earth, and parallels of declination are directly above parallels of terrestrial latitude. In consequence of the earth's rotation a star appears on the same meridian after an interval of a sidereal day. It may, therefore, be any distance up to 180° on either side of the meridian. The angle between any particular meridian and the declination circle of a star, measured along the celestial equator, is the *hour angle* of that star. If we suppose the arc thus intercepted to be 15°, the star will be one hour of sidereal time east or west of the meridian, for the whole 360° is described by the meridian in 24 sidereal hours, and 360° ÷ 24 = 15°.

It appears, therefore, that though the declination of a star is not altered by the earth's rotation, the hour angle of the star is constantly varying, as the observer is constantly moving towards it or away from it.

Declination and Right Ascension.—In the first system of celestial co-ordinates both measures are variable; in the second, one is variable,—in this both are practically invariable for a short period of time. Declination has already been defined. We have now to describe the point from which the other co-ordinate (right ascension) is reckoned. The ecliptic is the great circle produced by the intersection of the plane of the earth's orbit with the celestial sphere. This great circle cuts the equinoctial at two points, termed *equinoctial points* or *equinoxes*. At the time of the spring equinox every year, the sun is projected upon that part of the sky located by one of the points, and at the time of the autumn equinox, it occupies the opposite point.

The former is known as the 'first point of Aries,' and the latter as the 'first point of Libra.' Astronomers count right ascensions from the first point of Aries. Having described the starting point, we can define the right ascension of a star as the arc of the celestial equator intercepted between its hour circle and the first point of Aries. It is reckoned eastward from the starting point, and is expressed as an angle or a time. The latter method is usually employed. The celestial equator is supposed to be divided into twenty-four equal parts or hours, each of which is sub-divided into minutes and seconds. Stars on the line in the sky which passes from the north to the south celestial pole through the first point of Aries have for their right ascension oh. om. os. Expressed in angular measure, their right ascension is 0°. Every hour of right ascension is equivalent to an arc of 15°, the twenty-four sidereal hours being represented by 360°. It will be shown later that the equinoctial points are not fixed, but have a backward movement of $50''.2$ per annum. Neither is the plane of the earth's equator fixed in direction, though the change is very small in one year. In consequence of these movements, therefore, it is necessary to state the year in which observations of the right ascensions and declinations are made, for the positions are only absolutely accurate for that epoch.

Celestial Latitude and Longitude.—Declination is the celestial equivalent of terrestrial latitude, and right ascension of terrestrial longitude. We make a special note of this because it is natural to conclude that celestial latitude and longitude are terrestrial latitude and longitude projected upon the celestial sphere, whereas this unfortunately is not the case. The ecliptic is the primary circle for the system of co-ordinates under consideration; secondaries to it are called circles of celestial latitude. The latitude of a star is the arc intercepted between the star and the ecliptic, measured on a circle of latitude, and its longitude is the angle between the point where this circle cuts the ecliptic and the first point of Aries. It will be noticed that celestial longitudes are reckoned from the same point as right ascensions, though the former is counted along the ecliptic and the latter along the equator. Celestial longitudes are not, however, expressed in hours, minutes, and seconds, but in angles. Since the first point of Aries is not fixed, celestial longitudes alter from year to year, like right ascensions. Celestial latitudes can be considered as always the same, in this respect differing from declinations, which may vary as much as 47° in 26,000 years.

Graduated Lines and Arcs.—If a line divided into equal parts is moved in front of a fixed point and then brought to rest, the division near the point can be read off and the fraction of a division can be estimated. Thus, in Fig. 18 the reading indicated by the arrow is 15·3, the fraction ·3 being obtained by mentally dividing the division into ten parts and noticing that the arrow appears in front of the sub-division 3, counting from the division 15. It will be evident that there is a probability of error in such estimations. To obviate this, each division could be mechanically divided into ten parts, and these small divisions could be mentally sub-divided, but a limit is eventually reached beyond which it is impossible to carry the dividing. If we are dealing with arcs of circles instead of straight lines, this limit depends upon the radius of the circle. The circumference of a small circle cannot with advantage be divided up into more than 360 equal parts, each of which will represent one degree. In a large circle, however, one degree would be represented by an interval large enough to admit of sub-division, say, into sixty parts, each of which represents a minute of arc. On this account, instruments used for the measurement of small angles are fitted with large circles. Sometimes the circles are fixed to the instrument and move with it in front of a fixed point, but it is more usual to fix the circle and let a point fixed on the telescope move round its circumference.

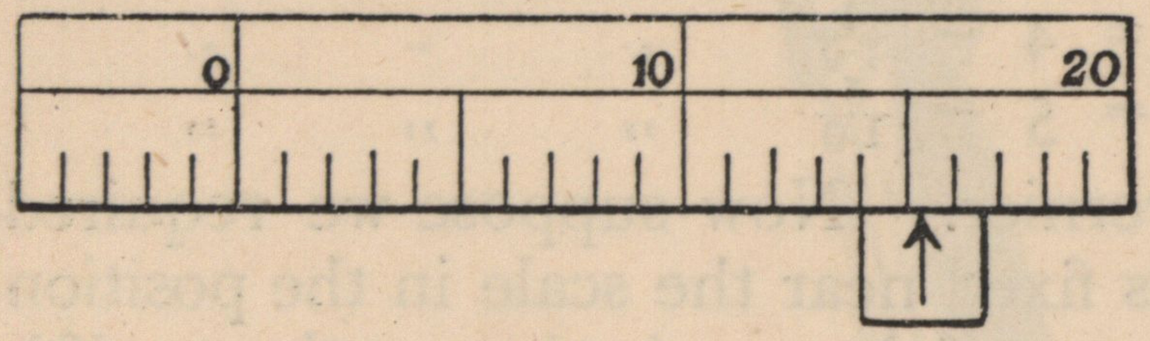


Fig. 18. Illustrating the reading of graduated scales.

The Vernier.—About 1630 a Frenchman named Vernier devised an arrangement by means of which fractions of divisions on a graduated line or arc could be very accurately measured. The principle of his method is as follows:—Let a line be divided into an *equal number of parts*, and let a length equal to nine of these parts be divided into ten parts as shown in Fig. 19. Then each

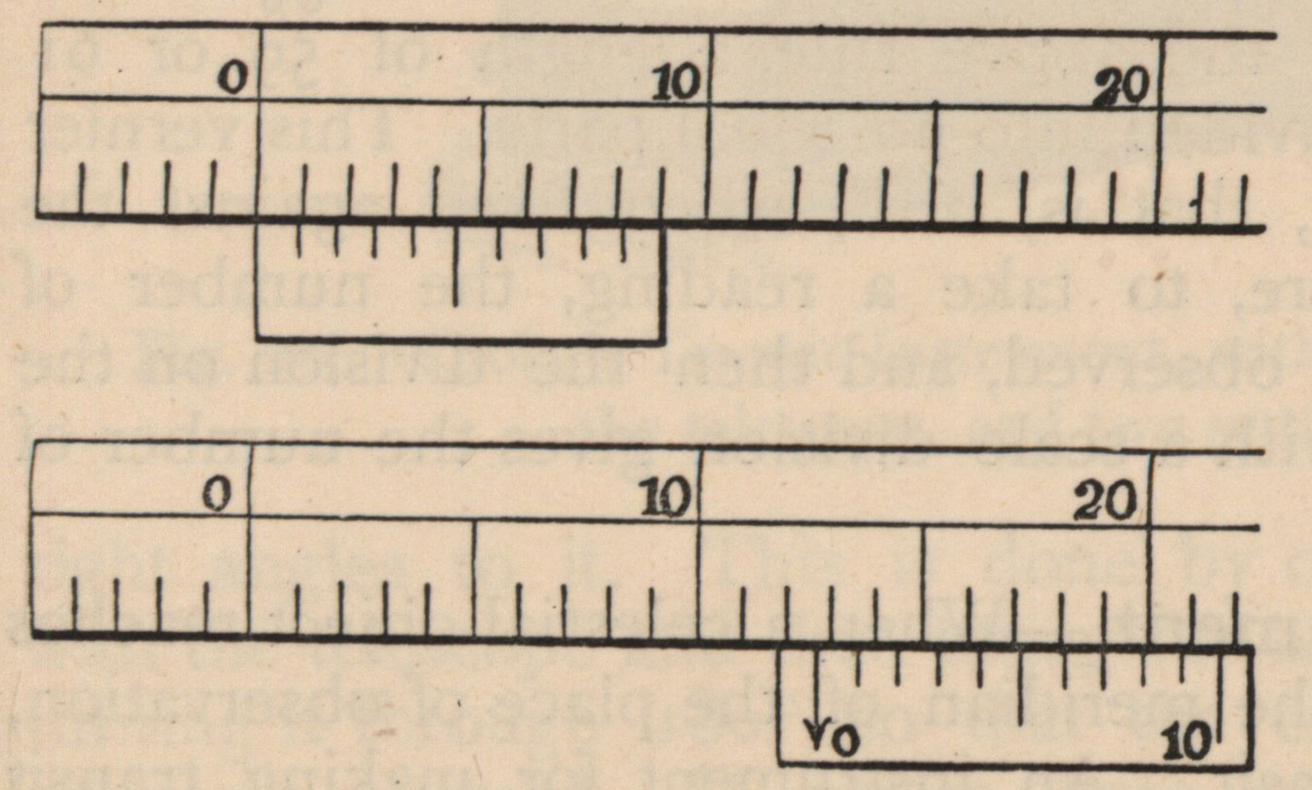


Fig. 19. Use of a Vernier.

of these divisions has a length one-tenth less than a division on the original scale. If we call the ten smaller divisions a vernier we have :—

1	division	on the	vernier	=	1	− $\frac{1}{10}$	division	of the scale
2	divisions	,,	,,	=	2	− $\frac{2}{10}$	divisions	,, ,,
3	,,	,,	,,	=	3	− $\frac{3}{10}$	,,	,, ,,
4	,,	,,	,,	=	4	− $\frac{4}{10}$	,,	,, ,,
5	,,	,,	,,	=	5	− $\frac{5}{10}$	,,	,, ,,

and so on to the end of the vernier. Now suppose we required the reading when the vernier is fixed near the scale in the position shown in the lower figure. The 0 of the vernier is past the twelfth division of the scale, and the question is, what is the sub-division with which it is in juxtaposition. On looking along the vernier, it will be seen that its division 7 is in a line with a division on the scale. The fraction between the twelfth division and the 0 of the vernier is therefore $\frac{7}{10}$, that is, ·7, and the reading is 12·7. If eleven divisions of the scale had been divided into ten equal parts, a vernier reading to $\frac{1}{10}$ of a scale division would again be obtained, but in this case the numbers on the vernier would have to run from right to left instead of left to right. The rule for constructing a vernier is stated as follows :—

'In general to read to the nth part of a scale division, n divisions of the vernier must equal $n + 1$ or $n - 1$ divisions on the limb, according as they read in opposite or similar directions.' The circles of telescopes are often divided into parts representing 20 minutes of arc. To construct a vernier, which in such a case would read to 20 seconds of arc, we first have to find the ratio which 20″ bears to 20′. Twenty minutes of arc are equal to 1,200 seconds of arc. Hence the ratio is as 1,200 : 20, that is, as 60 : 1. The vernier required has thus to read to $\frac{1}{60}$th of a scale division. Applying the above rule, a length of 59 or 61 divisions on the scale is divided into 60 equal parts. This vernier will read to $\frac{1}{60}$th of 20′, that is, 20″, when fixed against the graduated arc. As before, to take a reading, the number of degrees and minutes are observed, and then the division on the vernier which coincides with a scale division gives the number of seconds.

The Transit Instrument.—When a celestial object reaches its highest point it is on the meridian of the place of observation, and is said to be in transit. An instrument for making transit observations is shown in Fig. 20. It consists of a telescope having

an axle at right angles to its length, and capable of turning in U- or V-shaped bearings. These bearings are made exactly horizontal by means of a spirit-level (called a striding-level) of sufficient length to stretch from one bearing to the other. When the axis has been made horizontal, the telescope must be shown to be at

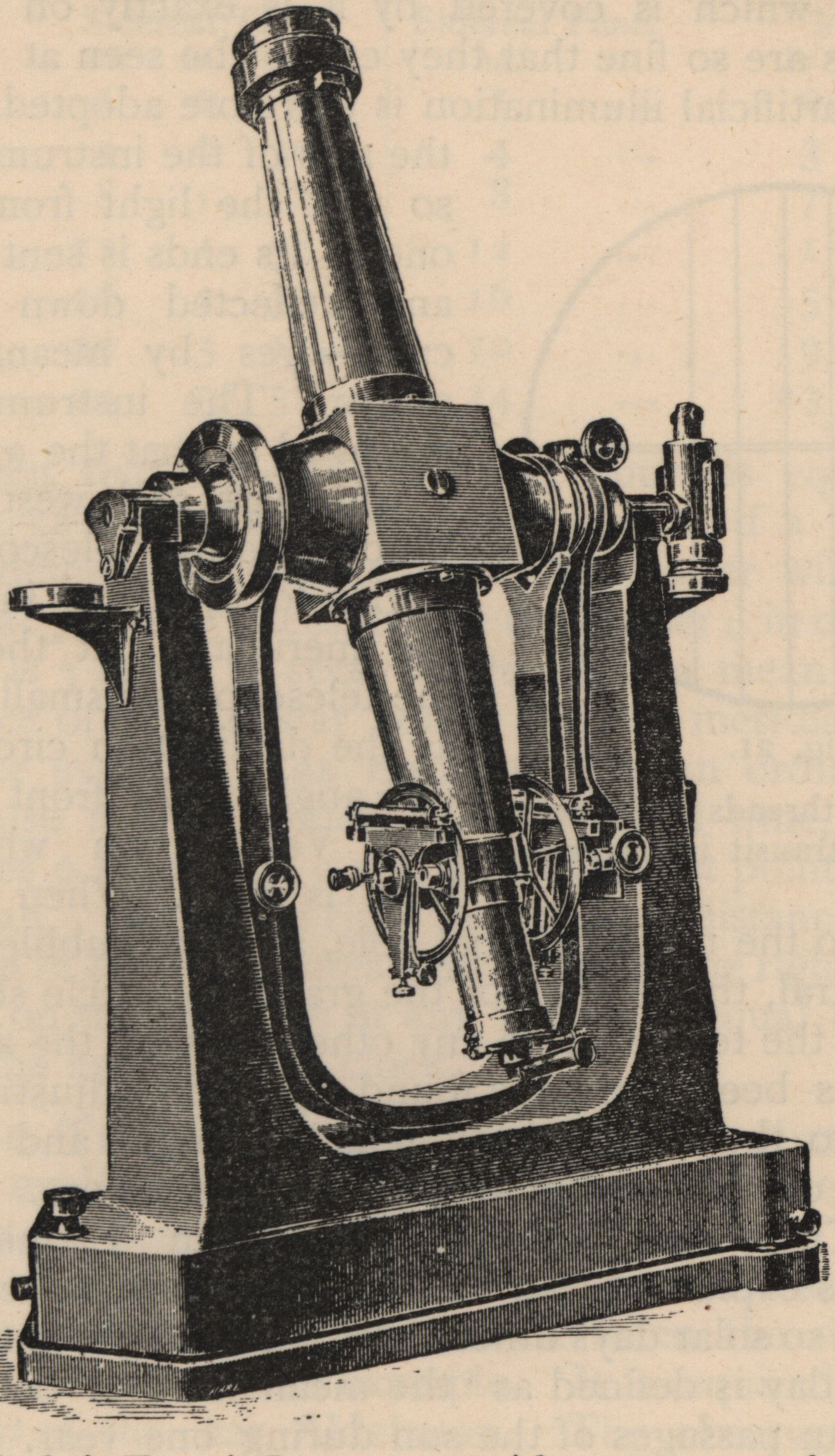


Fig. 20. Cooke's Transit Instrument, with arrangement for reversing the telescope, and two setting circles.

right angles to it. This is done by observing some fixed point with the telescope and then lifting the axis out of its supports, and turning it through 180°, so that the ends of the axis have their supports reversed. If, under these new conditions, the object occupies the same position in the field of view, the telescope is at

right angles to the axis; if not, an adjustment must be made to remedy the defect. On looking through a transit instrument, five or more vertical wires will be seen, and two horizontal ones. (Fig. 21.) The central vertical wire should be exactly in the meridian plane of the place in which the instrument is set up, so that a star which is covered by it is exactly on the meridian. These wires are so fine that they cannot be seen at night. Some method of artificial illumination is therefore adopted. In general, the axis of the instrument is hollow, so that the light from a lamp near one of its ends is sent into the tube and reflected down towards the cross-wires by means of a small mirror. The instrument must be arranged so that the axis shall have a true east and west direction, in which case the telescope, if at right angles to it, moves in the plane of the meridian. At the eye end of the telescope is a small circle, known as the declination circle, graduated into angles. In front of the circle is a Vernier, on which a spirit-level is fixed. When the telescope is pointed to the north celestial pole, and the bubble of the spirit-level is central, the reading of the graduated circle should be 90°. On moving the telescope to any other altitude, the angle through which it has been turned is found by again adjusting the spirit-level fixed to the Vernier until it is horizontal, and then noticing the reading on the fixed graduated circle as before.

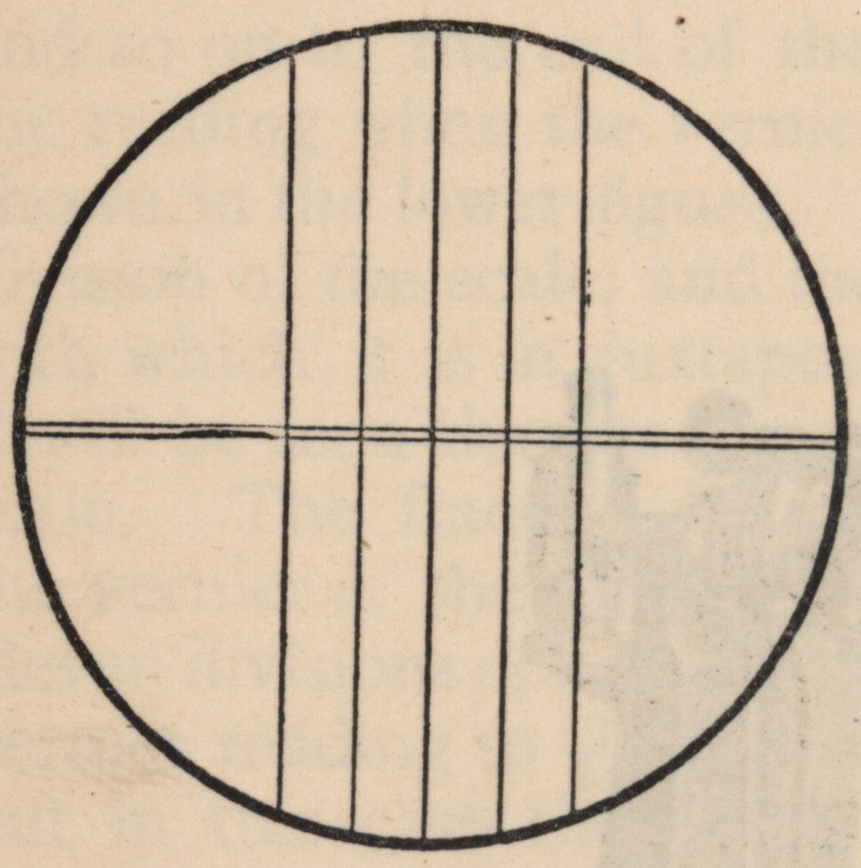


Fig. 21.

The wires or threads in the field of view of a transit instrument.

Mean Time and Sidereal Time.—In 'Elementary Physiography' it is explained that the sun does not move uniformly in the ecliptic, so solar days differ in length throughout the year. The mean solar day is defined as 'the mean interval between successive meridian passages of the sun during one year.' This is the unit of time adopted in every-day life. Mean time is defined as the time kept by an imaginary sun moving along the celestial equator at the average rate of the real sun in the ecliptic. When the stars are used to measure time, a very definite unit is obtained —the sidereal day, that is, 'the interval of time which elapses between two successive passages of the same star over the same meridian, and begins when the first point of Aries is on the

meridian.' There is a constant relation between mean and sidereal time, whereby one can easily be converted into the other. These equivalent intervals are given in the Nautical Almanac and other publications. A few of the values are given below :—

Mean Time.		Equivalents in Sidereal Time.			Sidereal Time.		Equivalents in Mean Time.		
hr.		hr.	ms.	sc.	hr.		hr.	ms.	sc.
1	...	1	0	9·8	1	...	0	59	50·2
4	...	4	0	39·4	4	...	3	59	20·7
8	...	8	1	18·8	8	...	7	58	41·4
12	...	12	1	58·3	12	...	11	58	2·0
16	...	16	2	37·7	16	...	15	57	22·7
20	...	20	3	17·1	20	...	19	56	43·4
24	...	24	3	56·3	24	...	23	56	4·1

It will be seen that a mean day of 24 hours is equivalent to 24 hrs. 3 mins. 56 secs. of sidereal time. Hence, if a mean time clock and a sidereal clock start together, the latter will make the round of its dial 3 mins. 56 secs. before the former ; in other words, a sidereal day is 3 mins. 56 secs. shorter than a mean solar day. In consequence of this, a star comes on the meridian 3 mins. 56 secs. earlier every day, as measured by an ordinary clock. Astronomers use a clock which keeps sidereal time, that is, it always indicates o hr. o min. o sec. when the first point of Aries is on the meridian. And since right ascension is distance from this point expressed in hours, minutes, and seconds, the right ascension of any object on the meridian at any instant is equal to the time indicated by the astronomical clock.

Use of the Transit Instrument.—From what has been said, it will be evident that the right ascension of a celestial object can be accurately determined by means of a transit instrument and a clock keeping sidereal time, and declinations can be found by taking the reading of the transit circle when the object is on the meridian. Let us take an example. It is required to find the right ascension of the star Aldebaran. The observer takes his seat at the transit instrument and sets the telescope at the proper elevation for the star a short time before that at which it transits. He writes down the hour and minute indicated by the sidereal clock and counts the seconds as he hears the pendulum beat them. The star enters the field of view, and, when it is covered by the first wire, the second and fraction of a second is called out and written down by an assistant, the same being done for all the

wires. An expert observer can mentally divide a second into ten parts, and he calls out the fraction of a second at which, in his opinion, the star crosses each wire. The following is the result of an observation made in this manner:—

Time of transit across			1st	wire	4	hours	27	mins.	9	secs.
,,	,,	,,	2nd	,,	4	,,	27	,,	21	,,
,,	,,	,,	3rd	,,	4	,,	27	,,	33	,,
,,	,,	,,	4th	,,	4	,,	27	,,	45	,,
,,	,,	,,	5th	,,	4	,,	27	,,	57	,,
				Mean	4	,,	27	,,	33	,,

The right ascension (R.A.) of Aldebaran is thus 4 hrs. 27 mins. 33 secs. Suppose this value to be previously known, then the error of the sidereal clock can be found by comparing it with the time indicated by the clock when the star is crossing the meridian. If the error of a mean time clock or watch is required, the same kind of observation is made, the mean time being converted into sidereal time by means of conversion tables. The right ascensions and declinations of thousands of stars have been found by astronomers and catalogued. These data are thus very similar to the latitudes and longitudes of places given in good atlases.

The Chronograph.—The method of observing transits described in the preceding paragraph is known as the *eye* and *ear* method. An instrument by means of which the times of transit can be much more accurately recorded is the chronograph, in which an electric current is utilised. The instrument used at South Kensington is thus described:—'A metal cylinder is covered with cloth, over which a piece of paper can be stretched, and is made to revolve by means of a clock, which is regulated by vanes. Below the cylinder and parallel to it is a screw carrying two electro-magnets, which is made to rotate by the same clock which drives the cylinder. The armature of each electro-magnet is connected with a pricker for marking the cylinder. One of the electro-magnets is connected with the sidereal clock in such a way that a current is sent through it every second, and the other is connected with a key, by means of which the observer can send a current through it at any instant. All the connections being made and the clock started, the clock magnet traces a spiral of pricks on the paper at intervals of about half an inch, a double space being left at the end of each minute. When a transit observation is made a series of extra pricks is made on the

cylinder parallel to the others by means of the key. The time at which each of the pricks was made is then ascertained by first counting the number of whole seconds which have elapsed since the last double space, and then measuring the distance of the prick from the beginning of the last second, which gives the fractions of a second. When the apparatus is started, the hour and minute is marked on the first double space.'

The Equatorial Telescope.—If the base of a theodolite is tilted until it lies in the plane of the equator instead of the plane of the horizon, then the telescope, when perpendicular to the base, will point to the celestial pole instead of the zenith. And if the telescope is fixed in any position out of the perpendicular, it will describe a circle round the celestial pole when the base is rotated. But, owing to the rotation of the earth, the stars appear to describe circles round the poles of the heavens; hence, to keep the telescope pointed towards any star throughout the diurnal rotation, it is only necessary to point the telescope towards the star and give the base a motion equivalent to the rate of movement of the celestial sphere by means of some clockwork arrangement. This is the principle utilised in the mounting of most large telescopes. (Fig. 22.) On the top of an upright stand rests an iron piece which points towards the celestial poles, and is therefore parallel to the earth's axis. This is known as the *polar axis* of the equatorial telescope. In a cylindrical hole bored through it turns a strong iron cylinder, at the bottom of which is fixed a disc graduated at the edge. The disc, known as the *hour circle*, being at right angles to the polar axis, is in the plane of the equator. It is divided into hours

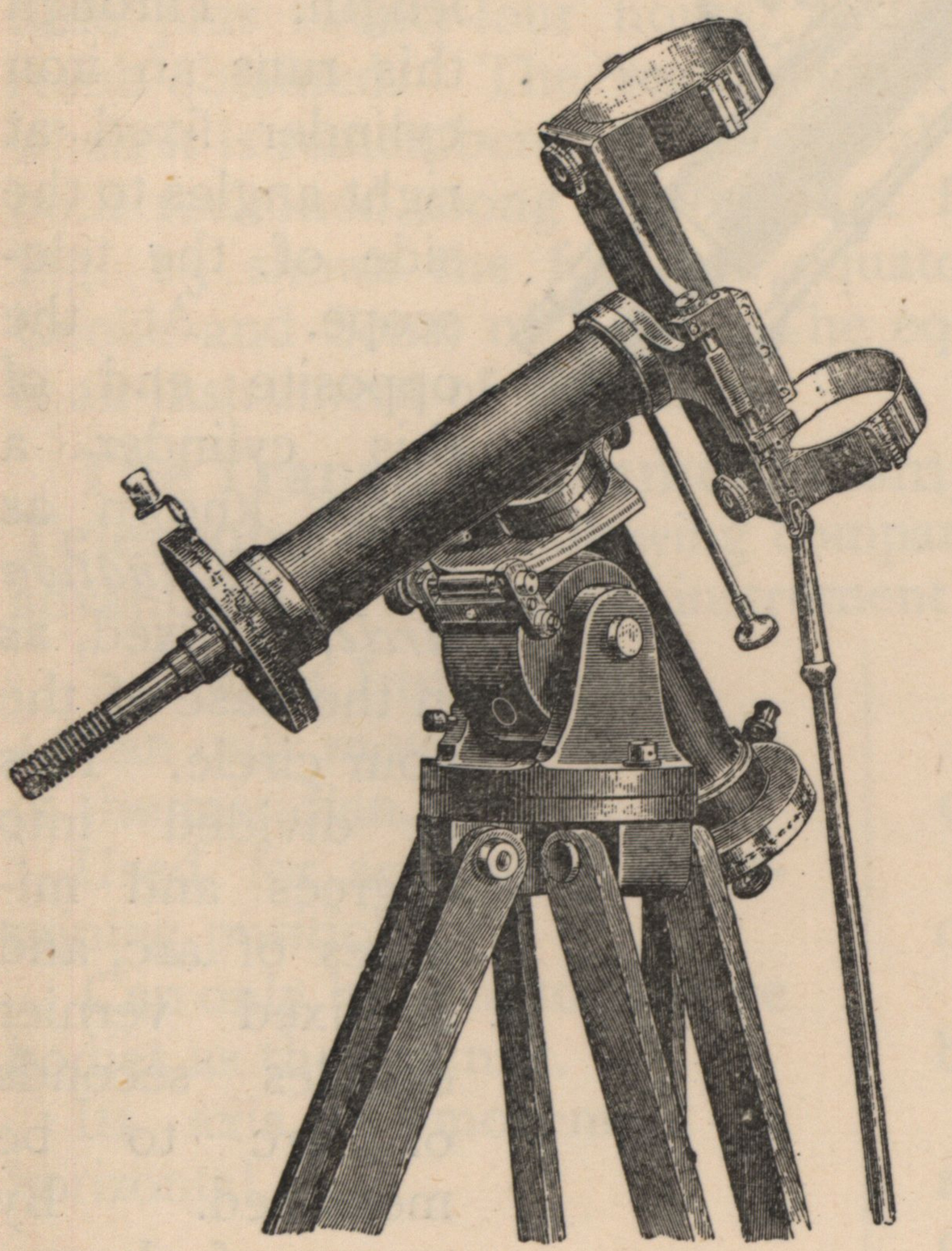


Fig. 22. Cooke's Equatorial Mounting on Tripod Stand.

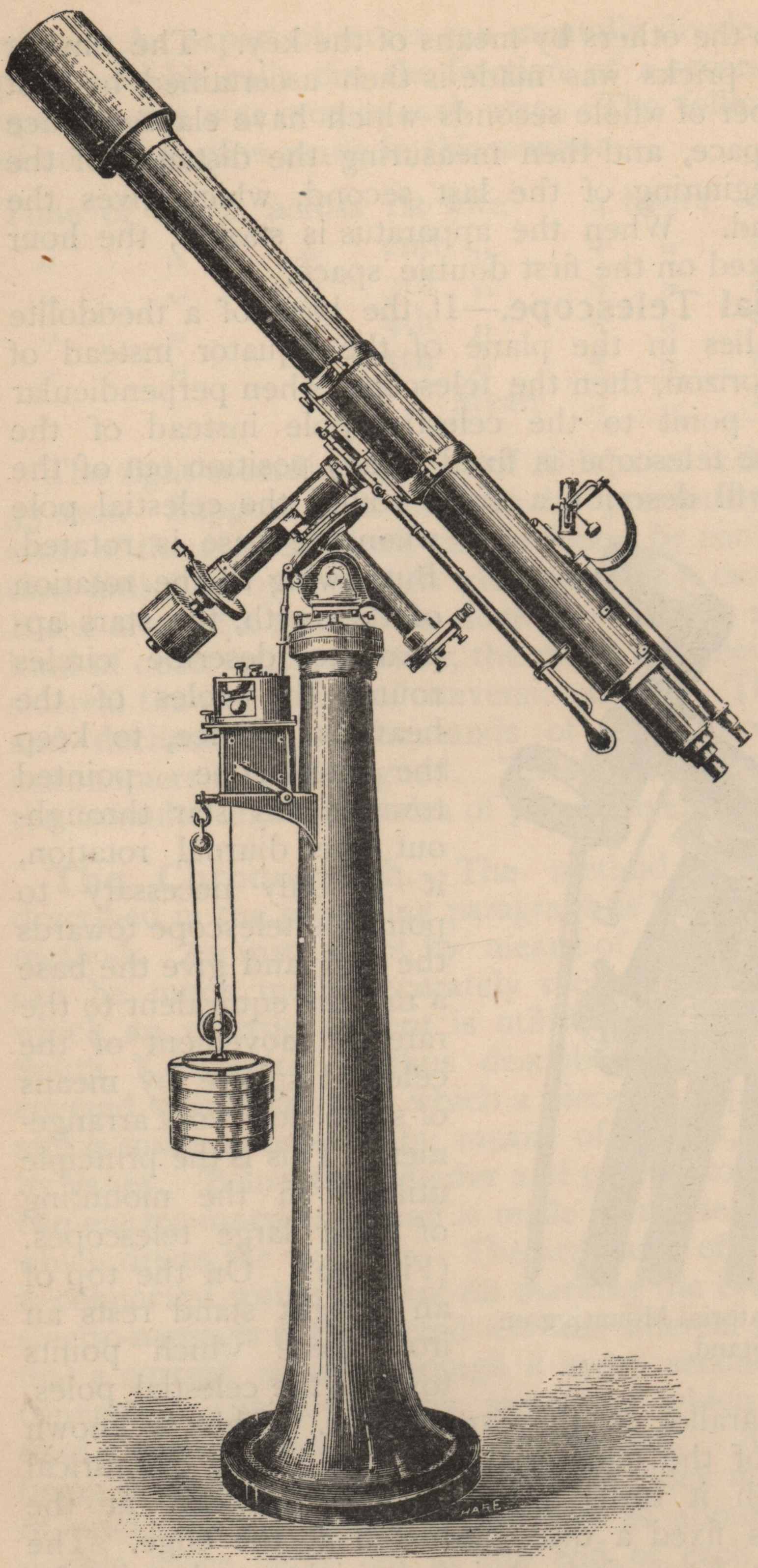


Fig. 23. Cooke's form of Astronomical Telescope, mounted equatorially, with driving clock attached.

and minutes, and a fixed vernier enables seconds to be read off. To the top of the iron cylinder is fixed another piece of iron similar and at right angles to the polar axis, and, like it, bored in the direction of its length. Through this runs an iron cylinder fixed at right angles to the side of the telescope. At the opposite end of this cylinder a circle, known as the *declination circle*, is fixed, as in the case of the hour circle. This is divided into degrees and minutes of arc, and a fixed vernier enables seconds of arc to be measured. By means of clamps, the telescope can be fixed in right ascension, or in declination, or in both co-ordinates. Consider first that it is fixed parallel to the polar axis.

It then points upward towards the north celestial pole. Now let the instrument be moved until the declination circle indicates that the telescope is 30° from the pole. Then if it is clamped in this declination it can be made to describe a circle of 30° radius round the pole by turning the hour circle. This movement is performed by a clockwork arrangement, so when the telescope has been directed towards an object, to keep the object in the field of view, it is only necessary to set the driving clock in action. What is more, any object can be easily found when its right ascension and declination and the sidereal time are known. The declination circle is first set so that its reading at the vernier is equal to that of the object. The right ascension is then subtracted from the sidereal time, or the sidereal time plus twenty-four hours, and the hour-circle is set to the result obtained. The reason for doing this will be understood when it is remembered that sidereal time and right ascension are both reckoned along the equator from the first point of Aries. Fig. 23 shows the form of equatorial constructed by Messrs. Cooke and Sons, of York. The equatorial at South Kensington is an instrument of this kind.

The Transit Instrument Compared with the Equatorial Telescope.—The following comparative table shows the relative advantages of the transit instrument and equatorial telescope :—

Transit Instrument.	Equatorial Telescope.
Can only move in the plane of the meridian.	Can be pointed to any part of the sky.
Used for accurately determining positions.	Used for investigating the celestial bodies themselves.
Can only be used to observe bodies as they transit.	Can be used to observe bodies continuously.
Its axis of movement is horizontal.	Its polar axis is elevated to an angle equal to the latitude of the place of observation.

The Micrometer Eye Piece.—This is an accessory to the telescope by means of which small arcs in the sky are measured. Several kinds of the micrometer eye-piece are in use. The simplest consists of two parallel wires, one or both of which can be moved to and fro. The moveable wire is fixed to a sliding piece, which is put in motion by turning a screw. The head of the screw is usually a metal disc about the size of a halfpenny. graduated on its edge into 100 equal parts, and touching the edge is a fixed

point or vernier. If the thread of the screw is evenly cut, the separation of the wires for one complete turn of the head is always the same. At right angles to the two parallel wires, two others, very close together, are fixed. A Ramsden or positive eye-piece is used to view the wires, just as in the case of the wires of the transit instrument. When the moveable wire and the parallel fixed wire are together the reading on the graduated screw-head should be zero. To measure the angular distance between two objects, say two stars, the micrometer is turned in the telescope until the stars lie within the two close fixed wires. The fixed wire at right angles to these is then made to cover one of the stars, and the head of the screw is turned until the moveable wire is over the other star. The number of turns and parts of a turn required to produce the proper separation is noted. We thus get the distance between the stars in terms of revolution of the screw head. If, therefore, the angle on the celestial sphere equivalent to one revolution of the head is known, the angular distance between the two stars can be found. To determine this value, advantage is taken of the fact that the arc described by a star in a given interval of time is always the same. A star on the celestial equator passes over an arc of $15''$ in one second of time. If, when the wires are separated by ten turns of the screw-head, an equatorial star take 45 seconds to pass from one to the other between the close fixed wires, we know that the arc is $15'' \times 45$, that is, $675''$ or $11' 15''$. This angle is equivalent to ten revolutions, therefore one revolution is equivalent to $1' 7''$.

It is by means of a micrometer like that above-described that the angular diameters of the sun, moon, and planets, or the distances between double stars, are measured.

The Decomposition of Light.—The action of a prism on a beam of light has already been described. The same decomposition of white light into colours occurs when a beam falls upon a surface upon which a large number of fine lines are ruled at equal distances apart. This means of dispersion is known as a *diffraction grating*. The lines are usually ruled upon a piece of polished metal, and vary in number from 1,000 to 17,000 in the length of an inch. The dispersive power of a grating having 17,000 lines to the inch is very great, that of a prism spectroscope increases with the number of prisms employed. Gratings are sometimes formed by ruling lines on silvered glass surfaces, in which case the beam of light passes through the lines and emerges decomposed on the other side. So far we have simply explained

the action of dispersion-pïeces on light. We have now to trace the development of the spectroscope from this principle. It was found by Wollaston that if a slab of light fell upon the prism instead of a cylindrical beam, a much purer spectrum was obtained. This follows from the fact that a spectrum is made up of coloured images of the hole through which the beam passes. If the hole is circular, an infinite number of circular images overlap one another, and a coloured strip having rounded ends is produced by the dispersion-piece; if it is a line, an infinite number of lines overlap; if it is a distant point, a coloured line of light is produced by the overlapping of an infinite number of points, each of a slightly different colour from its neighbours. After Wollaston, Fraunhofer discovered that considerable advantage was gained by using a small telescope to view the spectrum.

The Simple Spectroscope.—The essential parts of a spectroscope are (1) a slit to limit the width of the beam of light, (2) a prism or diffraction grating to decompose the light, (3) a small telescope to view the spectrum. The plan of such an instrument is shown in Fig. 24. The slit consists of two pieces of hard metal having fine edges parallel to each other. By means of a screw, the edges can be made to approach or recede, the width of the slit being thereby decreased or increased. At the

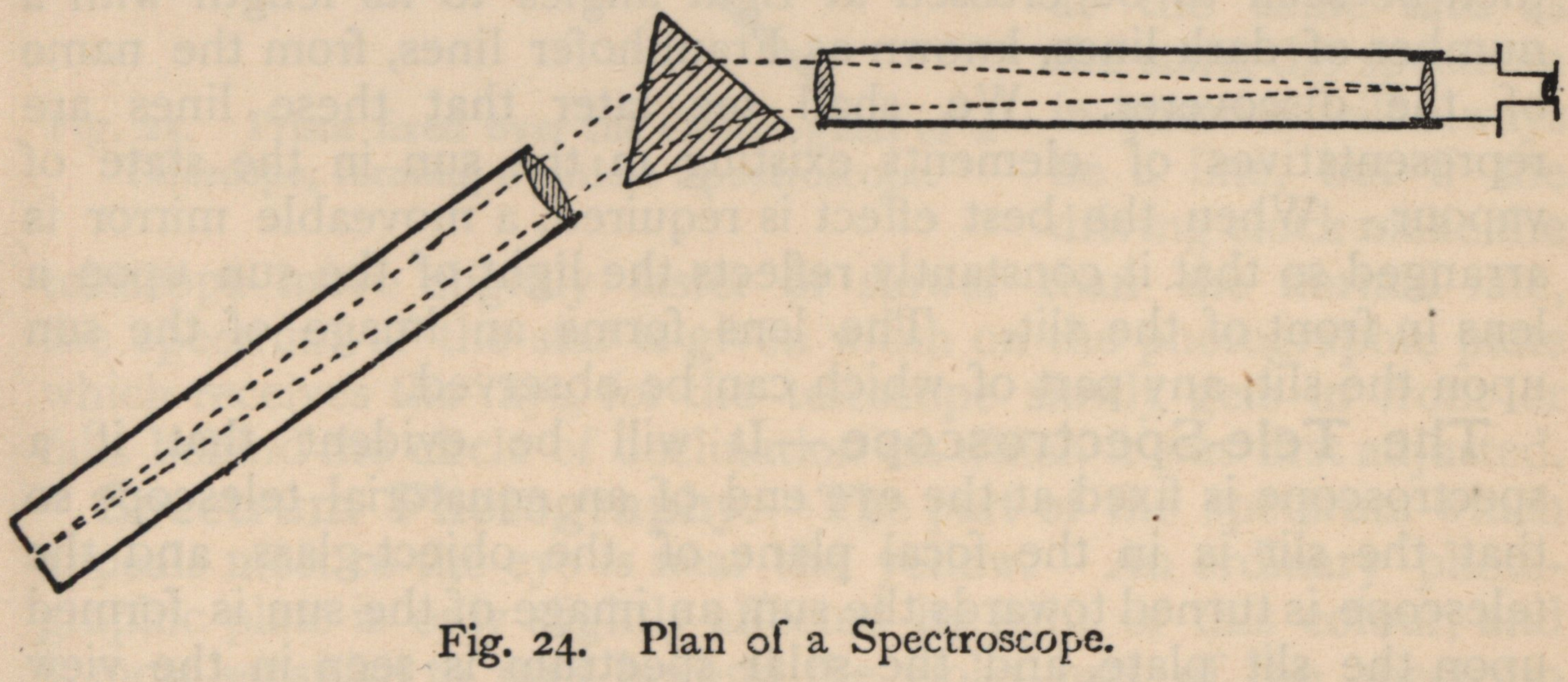


Fig. 24. Plan of a Spectroscope.

opposite end of the tube (known as the collimator) in which the slit is fixed, is a lens of such a focal length that the slit is exactly at its principal focus. In consequence of this, light which enters the slit emerges from the lens and falls upon the prism as a parallel beam. The view telescope is of the ordinary form, but in its eye-piece a cross-wire or a pointer of some kind is inserted and furnishes a fixed point of reference in the field of view.

Adjustments of the Spectroscope.—To adjust a spectroscope for use, a luminous flame is first placed about three inches from the slit. The prism is removed and the view telescope is brought in a line with the collimator and focussed upon the illuminated slit. The prism is then placed upon its table, and the view telescope is moved out of its original direction towards the base of the prism. The red end of a spectrum is first seen, and other colours pass across the field of view until the violet is reached. Now remove the luminous flame and put in its place a spirit lamp having a little salt upon its wick. The continuous strip of coloured light will disappear and a single yellow line will be seen. Turn the prism on its vertical axis while keeping this line in view. The line will move towards the red end of the spectrum, will reach a certain point and then turn back and begin to move in the opposite direction. The prism should be clamped in the position it occupies when the line is at its turning point—when it is as near the red end as it will go. This is known as the position of *minimum deviation*, and it can be shown that the spectrum is then seen at its best.

Observation of the Solar Spectrum.—In order to observe the spectrum of the sun it is sufficient to turn the adjusted spectroscope towards the sky. The coloured strip will then be seen to be crossed at right angles to its length with a number of dark lines, known as Fraunhofer lines, from the name of the discoverer. We shall see later that these lines are representatives of elements existing in the sun in the state of vapour. When the best effect is required, a moveable mirror is arranged so that it constantly reflects the light of the sun upon a lens in front of the slit. The lens forms an image of the sun upon the slit, any part of which can be observed.

The Tele-Spectroscope.—It will be evident that if a spectroscope is fixed at the eye end of an equatorial telescope so that the slit is in the focal plane of the object-glass, and the telescope is turned towards the sun, an image of the sun is formed upon the slit plate, and the solar spectrum is seen in the view telescope. And since the driving clock keeps the equatorial following the sun, the spectrum can be observed at leisure. An arrangement of this kind, in which a spectroscope is used as an accessory to the telescope, is known as a tele-spectroscope. It can be used to observe the spectrum of any celestial object having a measurable disc. A star is always a point of light; its image on the slit plate is therefore a point, and its spectrum is a coloured

line. To give this line width, a cylindrical lens, that is, a lens the surfaces of which are parts of a cylinder instead of parts of a sphere, is inserted in front of the slit plate or the eye lens. A coloured strip then replaces the coloured line in the field of view.

The Object-glass Prism.—Fraunhofer used a prism in front of the object glass of his spectroscope in order to make visual observations of stellar spectra, and the method has been developed by Professor Pickering and Professor Lockyer for photographing these spectra. The light of a star is decomposed by passing through the prism and brought to a focus by the object glass. (Fig. 25.) The edges of the prism are placed east and west, so that the coloured line which represents the spectrum of the star lies in the direction of a declination circle. Now, if the telescope move exactly at the same rate as the stars, the spectrum in question will always be a line, but if the driving clock make the telescope move slightly faster or slower than the normal rate, the spectrum of the star is given width on the photographic plate which receives the rays, for the telescope slowly gets in front or falls behind the circle of declination on which it was first adjusted.

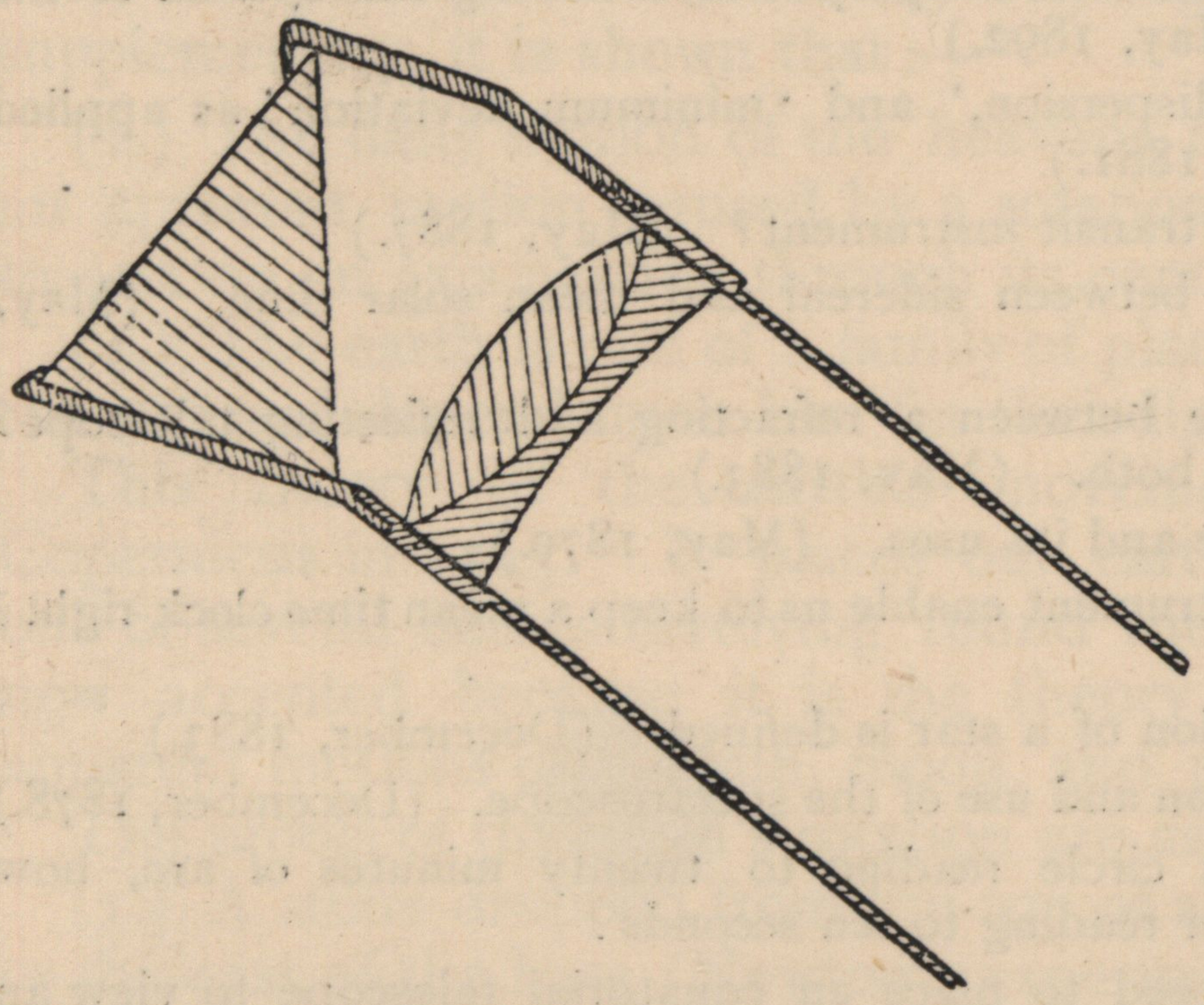


Fig. 25. Prism fixed over the Object-glass of a Telescope, forming a slitless Spectroscope.

Spectrum Photography.—The part of the spectrum which appeals most to the eye is near the yellow. An ordinary photographic plate is only slightly affected by light of this colour, and is most sensitive to rays beyond the violet part of the spectrum which are entirely invisible to us. If a photographic plate is placed in a proper slide at the eye end of a spectroscope, it receives the spectrum, and by treating the plate with the necessary chemicals, a permanent record of what the plate saw is obtained. To photograph the spectra of celestial objects, a small dark slide can be made to replace the eye-lens in a tele-spectroscope, or a dark slide can be placed in the focus of the object-glass having a

prism in front. In either case the violet and ultra violet parts of the spectrum are obtained upon the photographic plate. By using a special kind of sensitive plate, however, it is possible to photograph less refrangible parts of the spectrum, that is, parts nearer the red end.

QUESTIONS ON CHAPTER II.

1. State the various methods now employed in obtaining the spectra of the sun, stars, and nebulæ. (May, 1892.)

2. Explain the terms 'dispersion,' and 'minimum deviation' as applied to a beam of light. (May, 1881.)

3. What is the use of the transit instrument? (May, 1887.)

4. Explain the difference between sidereal and mean solar time. (May, 1885.)

5. What is the difference between a refracting and reflecting telescope? Describe the construction of both. (May, 1883.)

6. Describe a transit circle and its uses. (May, 1879.)

7. How does a transit instrument enable us to keep a mean time clock right? (December, 1889.)

8. Describe how the position of a star is defined (December, 1883.)

9. Describe the construction and use of the spectroscope. (December, 1878.)

10. If you were given a circle reading to twenty minutes of arc, how would you construct a vernier reading to ten seconds?

11. How would you proceed to place an equatorial telescope to view an object of which the right ascension and declination are known?

12. Describe the parallel wire micrometer and its use in determining the angular distance between two stars.

13. How are observations made with the transit circle, and what is their object? (December 1886.)

CHAPTER III.

THE SOLAR SYSTEM.

In the volume of 'Elementary Physiography' to which this is supplementary, it is shown that:—

(1.) The daily motion of the heavens from east to west is only an apparent motion caused by a rotation of the earth from west to east on an axis passing through its centre.

(2.) The earth is one of a family of planets which revolve round the sun and depend upon him for their light and heat.

This theory of the earth's movement was published by Copernicus in 1543. It places our earth in a minor position as one of several bodies revolving round the sun as a centre, and is now accepted because it is the theory that best explains the apparent motions of the sun, moon, and planets among the stars.

The proofs of the earth's rotation are as follows:—

(1.) A stone dropped from the top of a high tower falls slightly to the east of the base (Newton's experiment).

(2.) A long pendulum set vibrating has its plane of vibration apparently twisted round in the same direction as watch-hands in the northern hemisphere, and in the opposite direction in the southern hemisphere (Foucault's pendulum).

(3.) A well-balanced wheel, if set in rapid rotation in a vertical plane, has its plane of rotation apparently twisted round in the same direction as watch-hands in the northern hemisphere, and in the opposite direction to watch-hands in the southern hemisphere (Foucault's gyroscope).

Some of the consequences of this movement are:—

(1.) The occurrence of day and night, for only one half of the rotating globe can be turned towards the sun at one time.

(2.) A shot fired from a gun in the direction of higher latitudes is deviated towards the east; but if the gun is fired in the direction of lower latitudes, the shot is deviated towards the west.

(3.) Winds and ocean currents moving from the equator are deviated towards the east; those moving to the equator are deviated towards the west.

(4.) The bulging of the earth at the equator and flattening at the poles; for this is the form which would be assumed by the rotation of a semi-fluid mass.

That the earth revolves round the sun is proved by the following facts:—

(1.) The Annual Aberration of fixed stars. Owing to the motion of the earth in its orbit, combined with the velocity of light, all the stars seem to be displaced towards that point of the heavens in which the direction of the earth's motion tends at the moment. The amount of displacement, $20^{11}\cdot5$, is the *constant of aberration*.

(2.) The Annual Parallax of Fixed Stars. Although the stars are at enormous distances from the earth, some of them appear in a slightly different direction when observed at different times in the year. This variation would be impossible if the earth were at rest.

(3.) By observations with the spectroscope it has been directly proved that the earth revolves in an orbit, moving towards one part of the heavens at one time and in an opposite direction six months later.

(4.) Bodies in revolution, such as the sun and earth, move around their common centre of gravity, this point being at a distance from either body inversely proportional to the mass of the body. The sun's mass is 331,000 times greater than that of the earth. The common centre of gravity is, therefore, 331,000 times nearer the sun than the earth; in fact, it is inside the sun's surface.

The eastward movement of the sun among the stars, whereby our luminary appears to travel completely round the sky in a sidereal year, is a consequence of the earth's revolution, and in conjunction with the inclination of the earth's axis, it causes the varying lengths of days and nights, and the succession of the seasons.

The Solar System.—So far, the earth has only been considered as a moving observatory. It must now take a minor position as one of the sun's family of planets. The members of the solar system are grouped in this manner:—

(1.) The Sun; the central body.

(2.) Eight large planets named Mercury, Venus, The Earth, Mars, Jupiter, Saturn, Uranus, Neptune, this being their order of distance from the sun. A planet has been suspected nearer the sun than Mercury, and one more distant than Neptune.

(3.) A number of minor planets, or asteroids, revolving between the orbits of Mars and Jupiter, about 380 being now known. They probably represent a planet broken up in the course of formation.

(4.) The Satellites of the Planets. The Earth has one; Mars, two; Jupiter, five; Saturn, eight, and a system of rings; Uranus, four; Neptune, one.

(5.) Comets. About 700 have been recorded in historic time, but a much larger number must have been invisible.

(6.) A number of swarms of meteorites revolving round the sun like comets.

(7.) A ring of faintly luminous matter (the zodiacal light) extending round the sun, and probably consisting of innumerable meteoritic particles.

Stars and Nebulæ.—The countless stars with which the celestial world is sprinkled move together like bright spots upon a solid revolving sky, thus earning for themselves the name of 'fixed stars.' Objects are also frequently seen which do not remain fixed among the stars from night to night. These are members of our system. In addition to the bodies visible to the naked eye, the telescope reveals wisps and regions of cloud-like matter, known to astronomers as 'nebulæ.' The planets shine by reflected sunlight, but stars and nebulæ, like the sun, are self-luminous.

Different Kinds of Astronomy.—We have now enumerated the heavenly bodies, the study of which constitutes the science of Astronomy. It is found convenient to divide the science into several branches, in each of which different phenomena are studied, but all tending to the development of knowledge. There is *Gravitational Astronomy*, which deals with the heavenly bodies in the light of Newton's law of gravitation. *Theoretical or Mathematical Astronomy* is intimately connected with this. The scope of *Practical or Observational Astronomy* hardly needs defining. This branch includes the observations made by primitive mankind of the positions and motions of the 'orbs on high' as well as the delicate measures now made with the marvellous instruments at our disposal. *Descriptive Astronomy* began with the telescope, and has for its aim the study of the features of heavenly bodies, while *Astronomical Physics or Astro-Physics* chiefly considers their constitution, and has for its instruments of research, the spectroscope and the photographic camera.

Planets.—The ancients distinguished and called planets five bodies which moved among the stars, and named them Mercury, Venus, Mars, Jupiter, and Saturn. They also called the Sun and Moon planetary bodies. The moderns do not count the Sun and Moon as planets, but have added to the above list two faint bodies barely visible to the naked eye, and called them, respectively,



Fig. 26. Comparative dimensions of some Planetary Orbits.

Uranus and Neptune, besides a host of minor planets or asteroids. All the planets revolve round the sun in one invariable direction, which, if we could view them from above the plane of the ecliptic, would be seen to be opposite to that of the hands of a watch; each planet also rotates on an axis in the same direction. In order to see the motion of the planets in its greatest simplicity,

the student should conceive himself stationed at the sun. The stars would be seen fixed in the heavens at an infinite distance away, and the planets would be observed to move among them. (Fig. 26.)

Relative Sizes and Orbits of Planets.—The following illustration by Sir John Herschel gives some conception of the relative sizes and orbits of the planets:—'Choose any well-levelled field. On it place a globe two feet in diameter; this will

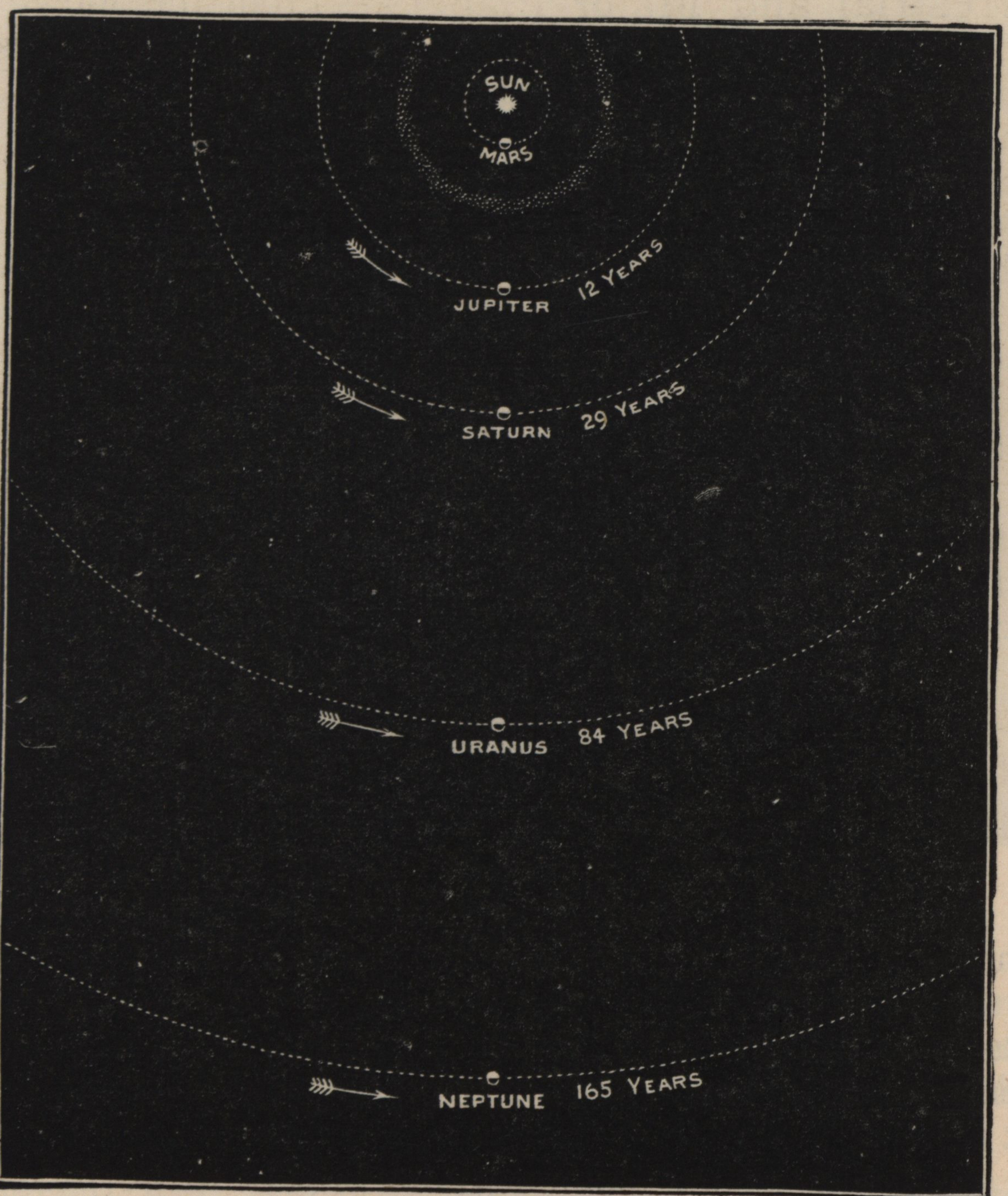


Fig. 27. Portions of Planetary Orbits from Mars to Neptune.

represent the sun. Mercury will be represented by a grain of mustard seed, on the circumference of a circle 164 feet in diameter for its orbit; Venus, a pea on a circle of 284 feet in diameter; the Earth also a pea on a circle of 430 feet; Mars, a rather large

pin's-head on a circle of 654 feet; the asteroids, grains of sand in orbits of 1,000 to 1,200 feet; Jupiter, a moderate-sized orange in a circle of nearly half a mile across; Saturn, a small orange on a circle of four-fifths of a mile; Uranus, a full-sized cherry or small plum upon the circumference of a circle more than a mile and a half; and finally Neptune, a good-sized plum on a circle about two miles and a half in diameter.' On this scale the nearest star would be 8,000 miles away. (Fig. 27.)

Terrestrial and Major Planets.—From the foregoing it will be seen that the planets are naturally divided into two groups. Our earth is one of four comparatively small planets, whilst Jupiter, Saturn, Uranus and Neptune are four much larger bodies. The bodies similar to the earth are called terrestrial planets, the members of the other group are called major planets. There are other considerations besides size which point to such a division of the members of our system. The terrestrial planets have high densities, are covered with water and air, and probably like the earth in physical constitution, they also have a comparatively small number of satellites and a slow velocity of rotation on their axes. The major planets are much less dense, their density not differing considerably from that of water; they have a much greater number of satellites revolving round them, and rotate more rapidly on their axes, hence their days are shorter than those of the terrestrial planets. It is also very probable that the major planets are at a high temperature, and emit a certain amount of light of their own.

Planetary Aspects.—Mercury and Venus—the two planets which travel round the sun within the orbit of the earth, are called *Inferior or Interior Planets.* Mars, the Asteroids, Jupiter, Saturn, Uranus and Neptune have their orbits outside that of the earth, and are called *Superior or Exterior Planets.* All the planets appear to move among the stars, but there is a marked difference in the behaviour of these two groups. When an inferior planet is between the earth and the sun, it comes on the meridian at the same time as our luminary, and is said to be in *inferior conjunction.* When the planet is on the opposite side of the sun, and the two bodies come on the meridian together, it is said to be in *superior conjunction.* A superior planet similarly situated with respect to the sun and earth is merely said to be in *conjunction*, but when the earth is between it and the sun, and the celestial longitude of the two bodies differs by 180°, the planet comes on the meridian

at midnight, and is said to be in *opposition* (Fig. 28). The angle between the two lines joining the centres of a planet and the sun to that of the earth is termed the *elongation* of the planet from the sun. The elongations of Mercury and Venus cannot exceed 29° and 47° respectively. The elongation of a superior planet may

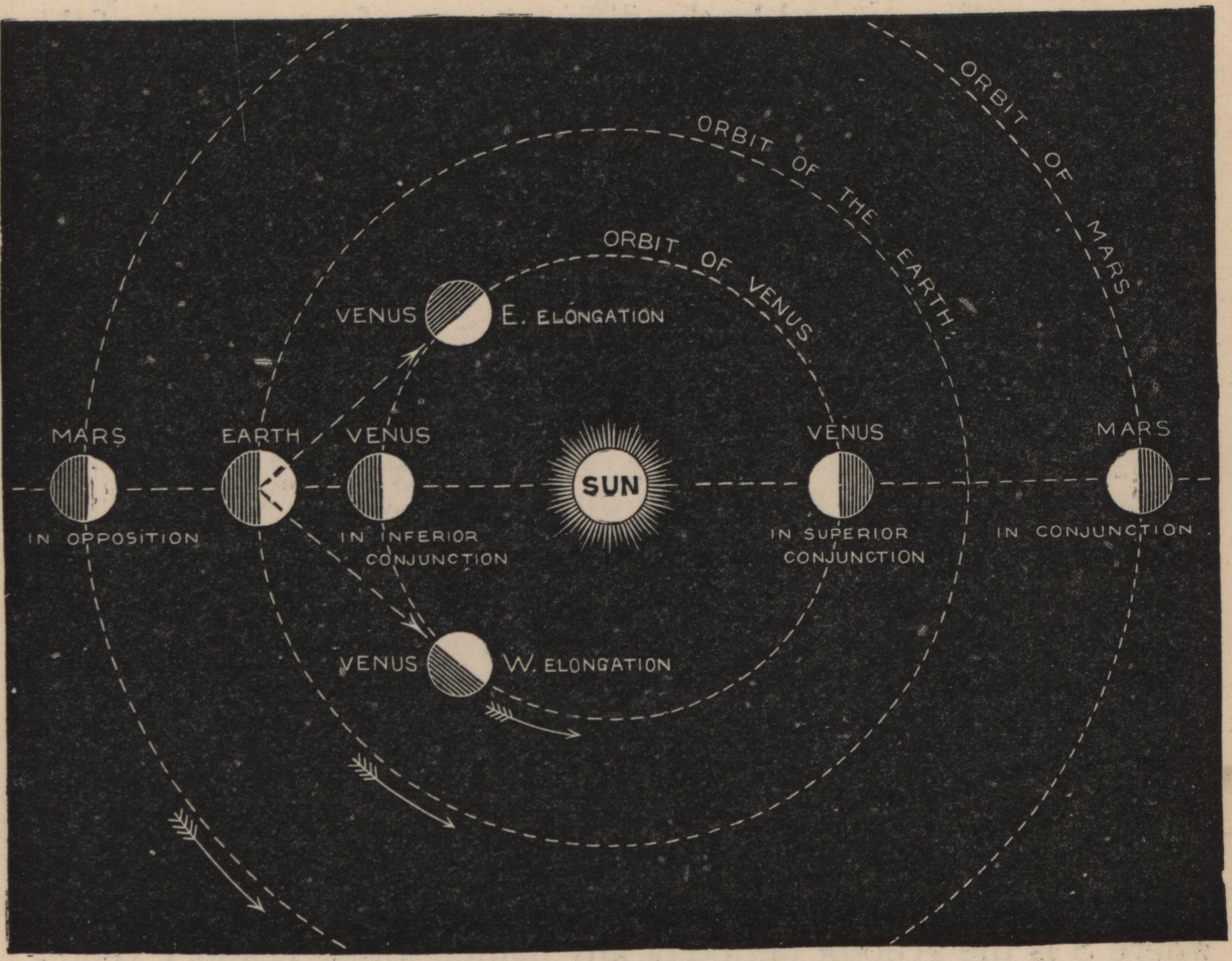


Fig. 28. Planetary Aspects.

have any value up to 180°, and, as in the case of an inferior planet, is east or west according to whether it is on the east or west side of the sun. A planet is in *quadrature* when its elongation is 90°.

Sidereal and Synodic Periods.—The Sidereal Period or Periodic Time of any planet is the time of its revolution around the sun, from a star to the same star again, as seen from the sun. Thus if the sun, a planet, and a star, are in an exact line at some particular time, the interval that elapses between this time and that of their coming in the same line again is the sidereal period. The movements of the planets appear more complicated because

they are seen from the earth, which is constantly changing its position. Each of the planets, when observed over comparatively long intervals of time with reference to the stars, appears to move forward, stop, go back a little, stop, and move forward again. When the motion is eastward, it is said to be *direct*, whilst *retrograde* motion is motion towards the west. This is only an apparent motion caused by the different rates of movements of the planets in their respective orbits as seen from the earth in motion; we thus get an apparent period, viz., the time taken by a planet to return to the same position with regard to the sun and earth. This is called the *synodic period* of a planet. The synodic periods of the chief planets are shown below.

Planet.	Synodic Period.
Mercury	116 days.
Neptune	367 ,,
Uranus	370 ,,
Saturn	378 ,,
Jupiter	399 ,,
Venus	584 ,,
Mars	780 ,,

These values are obtained by observation, and from them the sidereal periods are found by means of the equations

$$\frac{1}{S} = \frac{1}{P} - \frac{1}{E} \text{ and } \frac{1}{S} = \frac{1}{E} - \frac{1}{P}$$

where S is the synodic period of any planet, whilst E and P represent the sidereal periods of the earth and the planet under consideration. The use of this relation is best explained by an example. Suppose it is required to calculate the periodic time of Mercury. For an inferior planet the equation is

$$\frac{1}{S} = \frac{1}{P} - \frac{1}{E}$$

$$\text{That is } \frac{1}{P} = \frac{1}{116} + \frac{1}{365}$$

$$\text{Therefore } \frac{1}{P} = \frac{481}{42340}$$

And so P (Mercury) = 88 days.

In the case of a superior planet, $\frac{1}{P}$ and $-\frac{1}{E}$ change their signs.

Hence, to find the periodic time of Mars,

$$\frac{1}{780} = \frac{1}{365} - \frac{1}{P}$$

$$\text{That is } \frac{1}{P} = \frac{1}{365} - \frac{1}{780}$$

$$\text{Therefore } \frac{1}{P} = \frac{415}{284700}$$

$$\text{Hence P (Mars)} = 686 \text{ days.}$$

Form of Planetary Orbits.—By measuring the change in the sun's apparent diameter throughout the year, it has been found that the earth moves in an elliptic path or orbit. The orbits of other planets are similar in shape. This fact is expressed in what is known as Kepler's first law of planetary motions, viz.:

'The orbit of each planet is an ellipse, the sun being situated in one of the foci of each ellipse.'

This, and the two remaining Kepler's laws, will be considered in a future chapter.

Elements of an Orbit.—The size, form, and position of the orbit of a planet are completely known when the following facts have been determined:—

(1.) The Mean Distance.
(2.) The Eccentricity.
(3.) The Inclination.
(4.) The Longitude of the Ascending Node.
(5.) The Longitude of Perihelion.
(6.) The Mean Longitude at some epoch.

Mean Distances of Planets.—Since planets move in elliptical orbits, their distances from the sun are constantly varying. The mean distance is half the length of the major axis of the ellipse, that is, the semi-major axis. It is intimately connected with the periodic time in a manner to be described later. The

mean distances and periodic times of the chief planets are tabulated below.

	Mean distance from the Sun in Millions of Miles.	Sidereal period in Mean Solar Days.
Mercury	36	87·9
Venus	67	224·7
The Earth	93	365·2
Mars	141	686·9
Jupiter	483	4332·6
Saturn	886	10759·2
Uranus	1782	30686·3
Neptune	2792	60181·1

Eccentricity of an Orbit.—This is the ratio which the distance from the centre of the orbit to the sun bears to the semi-major axis; thus, in an ellipse of eccentricity $\frac{3}{4}$ or ·75, the distance from the centre of the ellipse to one of the foci is $\frac{3}{4}$ the length of the semi-major axis. (Fig. 29.) To construct an ellipse having any particular eccentricity a line of a convenient length is first drawn. Let this represent the major axis of the required figure. Bisect the line and divide each half into the number of parts indicated by the denominator of the fraction representing the eccentricity. Starting from the centre, count off on each side the number of parts given in the numerator of the fraction. The two points located in this manner are the two foci of the ellipse. Leaving comets and minor planets out of consideration for a time, the orbital eccentricities from the greatest to the least are as follows:

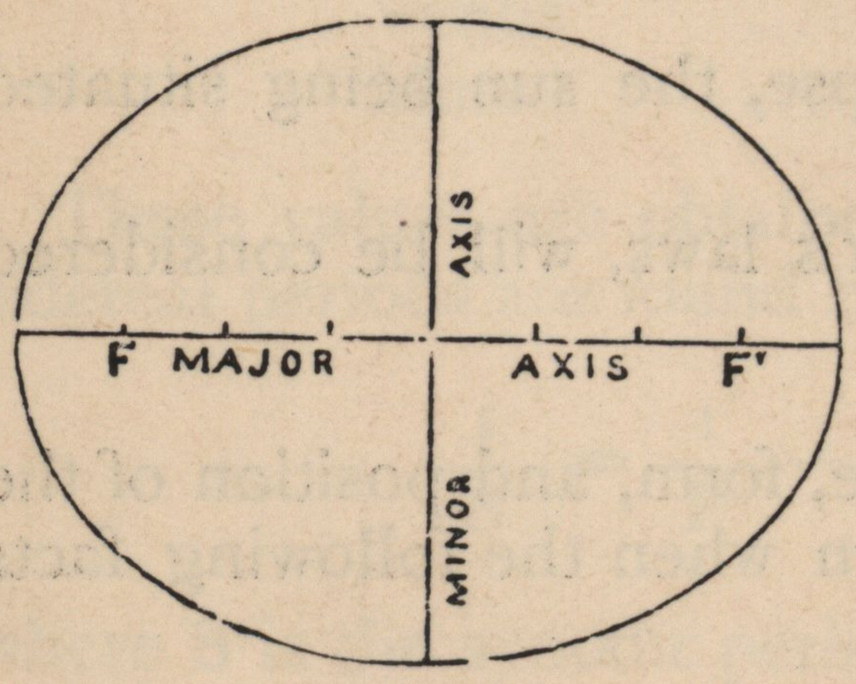


Fig. 29.

Elements of an Ellipse; F and F′ are the foci.

Planet.	Eccentricity.	Planet.	Eccentricity.
Mercury ...	·206 or $\frac{1}{5}$	Uranus ...	·046 or $\frac{1}{22}$
Mars ...	·093 or $\frac{1}{11}$	The Earth ...	·017 or $\frac{1}{59}$
Saturn ...	·056 or $\frac{1}{18}$	Neptune ...	·009 or $\frac{1}{111}$
Jupiter ..	·048 or $\frac{1}{21}$	Venus ...	·007 or $\frac{1}{143}$

Inclinations of Planetary Orbits.—The plane in which the earth revolves round the sun is the plane of the ecliptic. The orbits of the other planets do not lie exactly in this plane, in other words, the planets do not all revolve round the sun on

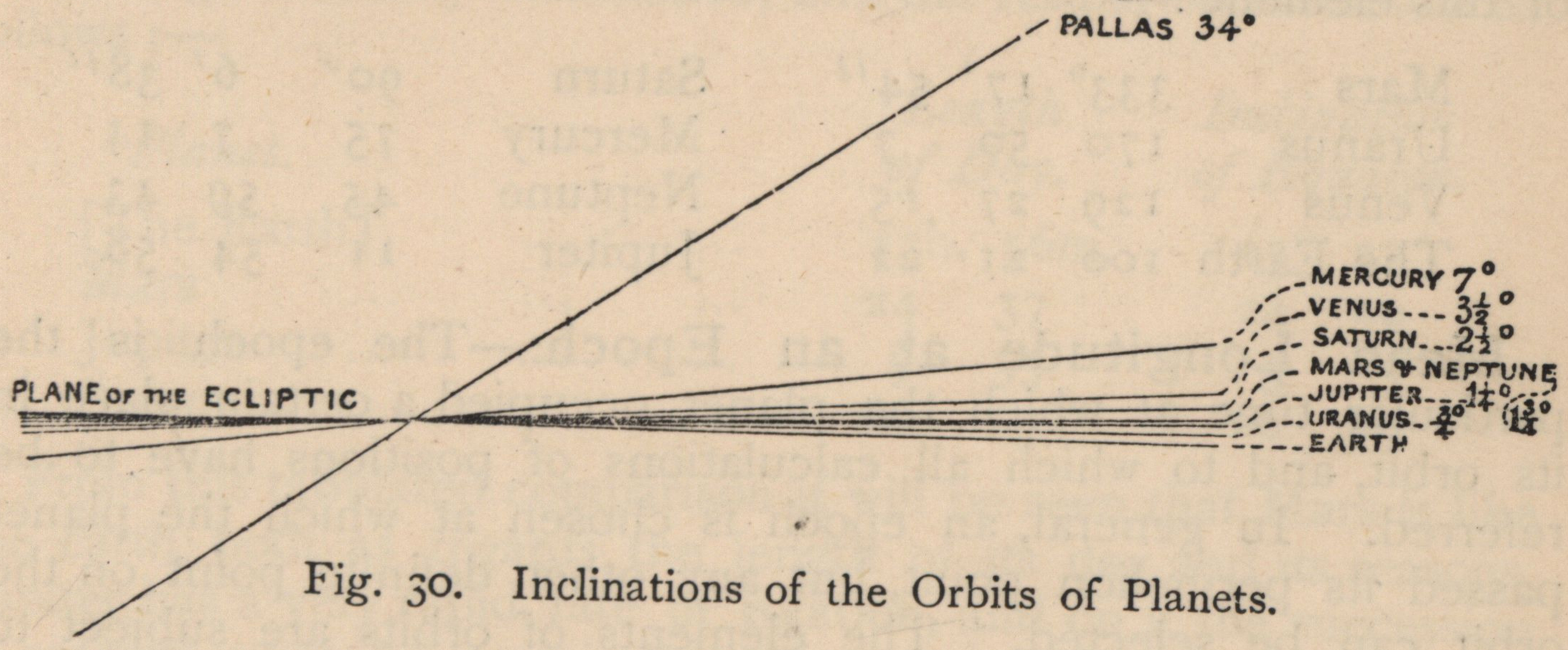


Fig. 30. Inclinations of the Orbits of Planets.

exactly the same level. By orbital inclination is meant the amount by which the plane of a planet's orbit is inclined to the plane of the ecliptic. (Fig. 30.) For the principal planets this element is approximately as follows:

Planet.	Inclination.	Planet.	Inclination.
Mercury ...	... 7° 0′	Neptune ...	... 1° 47′
Venus ...	... 3 24	Jupiter ...	... 1 18
Saturn ...	... 2 30	Uranus ...	... 0 46
Mars ...	... 1 51	The Earth	... 0 0

Longitude of the Ascending Node.—*Nodes.*—A planet whose orbit is inclined to the ecliptic plane describes half its path north of the plane and half south. The point at which it cuts the plane in passing from south to north is termed the *ascending* node, that at which the planet descends from north to south the *descending* node. The line joining these two points is the *Line of Nodes.* It is the common section produced by the cutting of two planes, viz., the plane of the planet's orbit and the plane of the ecliptic. The longitude of the ascending node is the angular distance of the node from the First Point of Aries, that is, angular distance from the point occupied by the sun at the spring equinox. The following table shows this element for the principal planets:—

Neptune	130°	6′	25″	Uranus	73°	13′	54″
Saturn	112	20	53	Mars	48	23	53
Jupiter	98	56	7	Mercury	46	33	0
Venus	75	19	52	The Earth	0	0	0

Longitude of Perihelion.—A planet is said to be in perihelion when it is at its shortest distance from the sun. The longitude of perihelion is the angular distance of the perihelion point from the First Point of Aries. The following are values of this element :—

Mars	333°	17′	54″	Saturn	90°	6′	38″
Uranus	170	50	7	Mercury	75	7	14
Venus	129	27	15	Neptune	45	59	43
The Earth	100	21	22	Jupiter	11	54	58

Mean Longitude at an Epoch.—The epoch is the particular time at which the planet occupied a certain place in its orbit, and to which all calculations of positions have to be referred. In general, an epoch is chosen at which the planet passed its perihelion point, but any other definite point on the orbit can be selected. The elements of orbits are subject to slight changes, but if the form at any given epoch is known and the rate of variation, then the form at a previous or future date can be estimated.

Mean Motion.—Direct and retrograde motions are respectively motions opposite to that of watch-hands, and in the same direction as watch-hands, to an observer north of the ecliptic. The motions of revolution and of rotation of all the planets are direct. Viewed from the earth, *direct* motion is eastward motion among the stars, and *retrograde* motion is motion towards the west. The mean motion of a planet or comet generally signifies the average angular distance in the sky which the body appears to pass over in a day.

So far we have only dealt with the orbits of planets. Let us now consider what these bodies are in themselves, as determined by the telescope.

Planetary Days and Seasons.—The period of rotation of a planet determines the length of the day, as in the case of the earth. It is found by observations of returns of the same spot or marking on the planet's disc to the same position. Hence, when the markings are not well defined the rotation period cannot be accurately found. The inclination of the equatorial plane of a planet to the plane in which the body revolves round the sun, determines the seasons. It is found by observing the paths followed by spots and markings on the disc, and can only be definitely settled when such markings are well visible. The error involved in the determination of the rotation periods of planets

showing only faint markings will be understood when we say that for the last four or five years it has been a matter of discussion whether Mercury and Venus rotate in about 24 hours, or 88 days and 224 days respectively. Only three planets permit of these data being accurately determined, and the results obtained are as follows :—

Planet.	*Length of Day.*	*Inclination of Equator.*
[The Earth]	23h. 56m.	23° 27′
Mars	24 37	24 50
Jupiter	9 55	3 5
Saturn	10 14	26 49

From this tabulated comparison it will be seen that Mars is like the earth, both as regards the length of its day and its seasons. Jupiter has a very rapid rate of rotation, and on it the succession of seasons must be practically unknown, for its equator is but very slightly inclined to the plane of revolution. Saturn has a day almost as short as Jupiter, and is distinguished by having very pronounced seasonal differences.

Orbits of Satellites.—With the exception of Mercury and Venus, all the planets are known to have satellites which accompany them in their journey round the sun. Some points referring to the motions and orbits of these bodies are as follows :—

(1.) *Distance from primary planet.*—This is known with a fair degree of accuracy. Mars has the nearest satellite, its distance being 5,850 miles; whilst the eighth satellite of Saturn, at a distance of 2,225,000 miles, is the most removed from its primary. The distance of our moon (240,000 miles) is a little less than that of Jupiter's second satellite, a little more than that of the attendant of Neptune, and twice as great as that of the nearest satellite of Uranus.

(2.) *The revolution periods* are known to fractions of a second. Our moon has a sidereal period of $27\frac{1}{3}$ days; the last satellite of Saturn, with a period of $79\frac{1}{2}$ days, is the only one with a longer period. Mars' first satellite performs a revolution in $7\frac{1}{2}$ hours; Jupiter's first in $1\frac{3}{4}$ days; Saturn's first in $22\frac{1}{2}$ hours, that is, about a day. The first satellite of Uranus has a period of $2\frac{1}{2}$ days, and the only attendant of Neptune revolves round its primary in a little less than six days.

(3.) *Eccentricity of Orbit.*—With the exception of the moon, and the seventh satellite of Saturn, all the satellite orbits have very small eccentricities, indeed, they are practically circles.

(4.) *Inclination of Orbit to Equatorial Plane.*—This datum is doubtful in cases where the position of the plane of the equator is undetermined, as in Uranus and Neptune. For other planets, all the satellites, except our moon and Saturn's outermost companion, move in planes which coincide with the equatorial planes of their respective primaries.

Bode's Law.—In 1772, a Professor at Wittenberg named Titius pointed out that the distances of the planets from the sun followed a more or less regular progression. Bode, of Berlin, afterwards took up the matter, and the statement of the connection between planetary distances is now known as Bode's Law. The discovery was to the effect that if four is added to each of a series of numbers in geometrical progression from o, the results obtained represent the relative distances of planets from the sun. In Bode's time, only five planets besides the Earth were known, viz., Mercury, Venus, Mars, Jupiter, and Saturn. The series held good for the first four in order of distances from the sun, but the fifth number had no planetary representative, Jupiter following on with the sixth. On account of this circumstance it was suggested that an undiscovered planet existed which would fill the gap. The series of numbers which led to this speculation is shown below :—

Planet.	Mercury	Venus	Earth	Mars	Minor Planets	Jupiter	Saturn	Uranus	Neptune
Geometrical Progression.	0	3	6	12	24	48	96	192	384
+ 4	4	4	4	4	4	4	4	4	4
Totals	4	7	10	16	28	52	100	196	388
Actual distances of the Planets, in terms of the Earth's distance	0·4	0·7	1·0	1·5		5·2	9·5	19·2	30·1

It will be seen that by dividing Bode's series by ten, the relative distances of the planets, calling the earth's distance unity, is obtained for all except Neptune. Hence, the earth's distance (93,000,000 miles) being known, it became possible to find the distance of any other planet by simple proportion.

Minor Planets.—A search for the body to fill up the gap between Mars and Jupiter indicated by Bode's Law led to the discovery of the first minor planet or asteroid in 1800. More of these bodies were soon found, and instead of a solitary planet revolving round the sun at a distance about three times as great as that of the earth, a host of extremely faint bodies, each revolving in an orbit of its own, has been discovered. The largest minor planet cannot be more than 300 miles in diameter, and some are probably no more than 10 miles, while the whole of them cannot have a bulk more than about $\frac{1}{4000}$ that of the earth.

Orbits of Minor Planets.—The minor planets do not move in concentric circles round the sun in the manner often represented in astronomical diagrams, the paths all differing from each other in many respects. The asteroid having the shortest average distance is at a little more than double the earth's distance from the sun, that most removed from our luminary has a mean distance of $4\frac{1}{4}$, the earth's mean distance being unity. The periods of revolution of these bodies are respectively 3·1 and 8·8 years. The mean eccentricity of the orbits of asteroids is 0·15, and is therefore much higher than the corresponding mean of the major planets—viz., 0·054. The mean inclination of the orbits to the ecliptic is 8°, while the mean inclination of the orbits of major planets is only $2\frac{1}{2}°$. The orbit of Pallas, one of the minor planets, is inclined 34° to the ecliptic. In general, the orbits greatly inclined to the ecliptic have also considerable eccentricity, though the converse of this does not hold good.

Comets and Meteors.—These two classes of bodies belonging to our system are intimately connected with one another, but differ from the planets and satellites both in their orbits and physical structure. Both revolve round the sun in a similar manner to the earth, but in paths which are usually very eccentric and considerably inclined to the ecliptic.

Cometary Orbits.—Halley discovered that a comet which appeared in 1682 revolved round the sun in a period of 76 years. He predicted the return of the comet in 1759, and his prediction was fulfilled. This proved that the comet moved in an elliptical

orbit. The periodicity of another comet was discovered by Encke in 1819. The time of revolution of this comet is $3\frac{1}{2}$ years, this being the shortest period at present known. An ellipse is a closed curve, so a body moving in an elliptical path comes back in time to the starting-point. When the two foci of an ellipse are

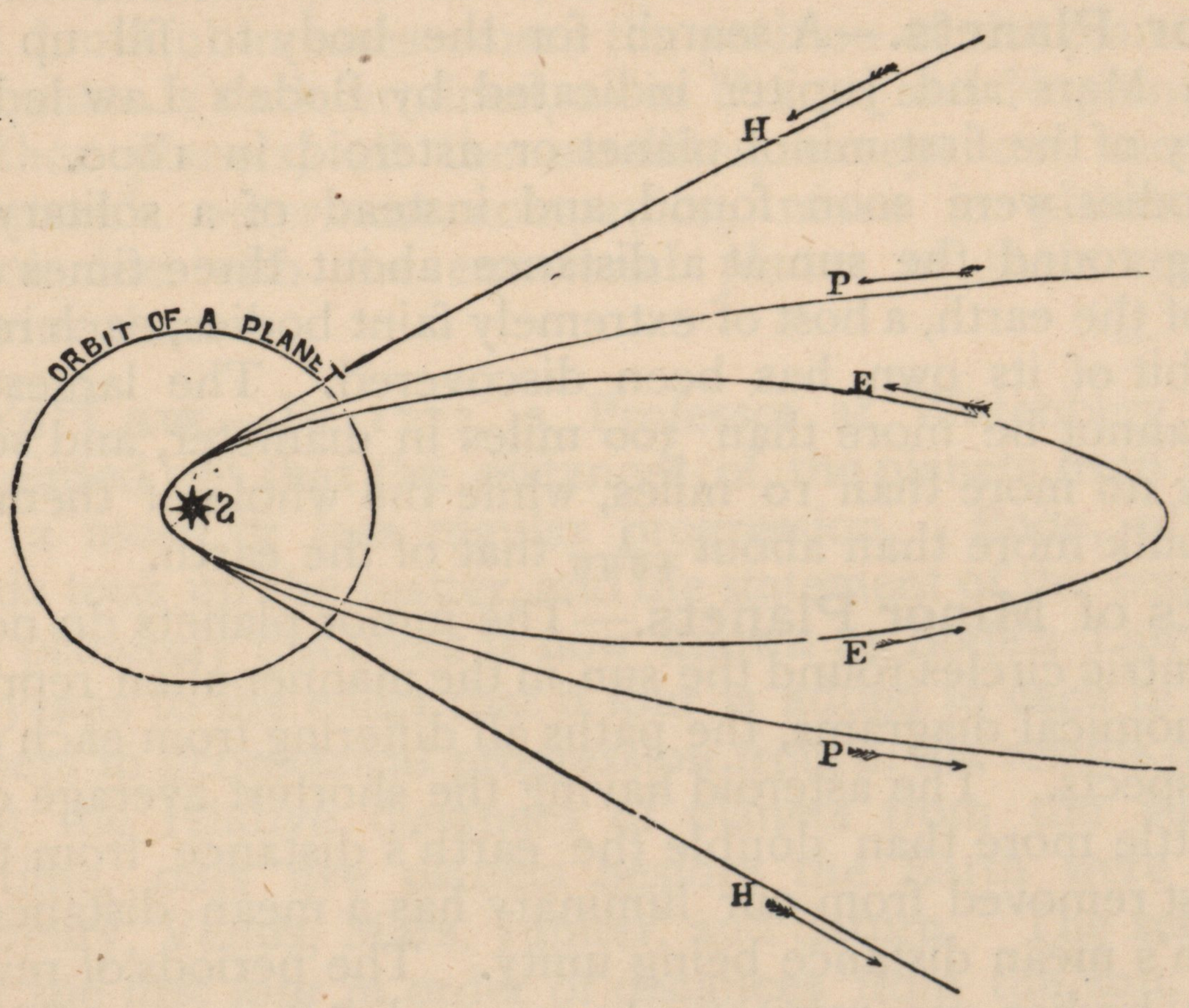


Fig. 31. The Sun (S) is in a focus of the planet's orbit, and also in one of the foci of the elliptical orbit E, the parabolic orbit P, and the hyperbolic orbit H.

separated by an infinite distance, a parabola is produced. (Fig. 31.) This is not a closed curve, so a body moving in a parabolic orbit never returns. Hyperbolic orbits possess the same peculiarity. The relative numbers of comets known to be moving in these orbits are as follows:—

Elliptical (periods less than 100 years)	...				...	28
Elliptical (periods more than 100 years)	...					25
Parabolic	...	...	...	...	...	220
Hyperbolic	...	...	...	...	...	6 (?)

Peculiarities of Cometary Orbits.—In general, the orbits of comets have very high eccentricities, though a few, having short periods of revolution, move in paths comparable with those of minor planets. The inclinations to the ecliptic have almost any value. Some orbits have but a slight inclination, others are

nearly at right angles to our plane of revolution. With a couple of exceptions, all comets having periods less than 100 years move round the sun in the same direction as the planets. Indeed, it seems to be established that elliptic orbits slightly inclined to the ecliptic are generally traversed by comets having *direct* motion. Other comets move in a *retrograde* fashion, in this respect differing from the planets and satellites. High eccentricities, great inclinations, and retrograde motion, are thus the distinguishing features of cometary orbits, and the orbits in which swarms of meteorites revolve round the sun are similarly characterised.

QUESTIONS ON CHAPTER III.

1. How does Foucault's pendulum experiment prove the rotation of the earth? (May, 1885.)

2. What are the chief elements of a planet's orbit? (May, 1884.)

3. What is the synodic period of a planet? (May, 1882.)

4. State what you know about the apparent movements of the stars, and the causes which give rise to them. (May, 1880.)

5. Draw the earth as seen from the sun, at the two solstices and equinoxes, showing the direction of its axis and the position of the north and south poles. (May, 1879.)

6. How are the daily and yearly apparent motions of the stars explained? (December 1887.)

7. What is the cause of the seasons? Contrast the seasons of Mars and Jupiter. (December, 1885.)

8. What is meant by the aberration of light? (December, 1884.)

9. How is the synodic period of a planet determined, and how can the sidereal period be deduced from it?

10. What is Bode's Law, and how did it lead to the discovery of the first asteroid?

11. Compare the orbits of minor, with those of major planets.

12. State some peculiarities of the orbits of comets.

13. Define Conjunction, Opposition, Quadrature, and Elongation.

CHAPTER IV.

THE DIMENSIONS OF THE SOLAR SYSTEM.

The Shape of the Earth.—The facts which indicate that the earth is not flat are as follows :—

(1.) The manner in which objects approaching from a distance appear to rise above the horizon, while receding objects seem to sink below it.

(2.) In travelling north from the equator, the elevation of the celestial pole is proportionally increased.

(3.) If three poles of the same height above a horizontal surface are placed in a row, the end of the middle pole projects above the line joining the ends of the two outer ones.

The facts which indicate that the earth is more or less globular are :—

(1.) The circular appearance of the visible horizon.

(2.) The shadow of the earth, as seen upon the moon during a lunar eclipse, always has a circular outline.

(3.) The intensity of gravity is very nearly the same all over the earth.

Relation of Arcs to Angles.— If, in any circle, the length of the arc which subtends a certain angle at the centre is known, then the length of the whole circumference can be found. Thus, if a length of five inches subtend an angle of 10 degrees, then the length of the circumference is given by the proportion,

$$10 \text{ degrees} : 360 \text{ degrees} :: 5 \text{ inches} : x \text{ inches}.$$

$$\text{Therefore } x = \frac{360 \times 5}{10} = 180 \text{ inches}.$$

In the same way, when the length of an arc on the earth's surface equivalent to a known number of degrees has been found, then the circumference can be calculated, and from this the diameter is deduced by dividing by $3\frac{1}{7}$. The theory requires,

therefore, that we should know (1) the length of an arc of a great circle with considerable accuracy, and (2) the angular distance between the extremities of the arc.

Trigonometrical Ratios.—The measurement of the first of these requirements will be better understood after a brief statement of some of the relations between the sides and angles of a triangle. In trigonometry, certain names are used to define the ratios between the sides of a triangle. Thus, let A B C (Fig. 32) be a right-angled triangle having sides *a*, *b*, *c*, named after the angles which they subtend.

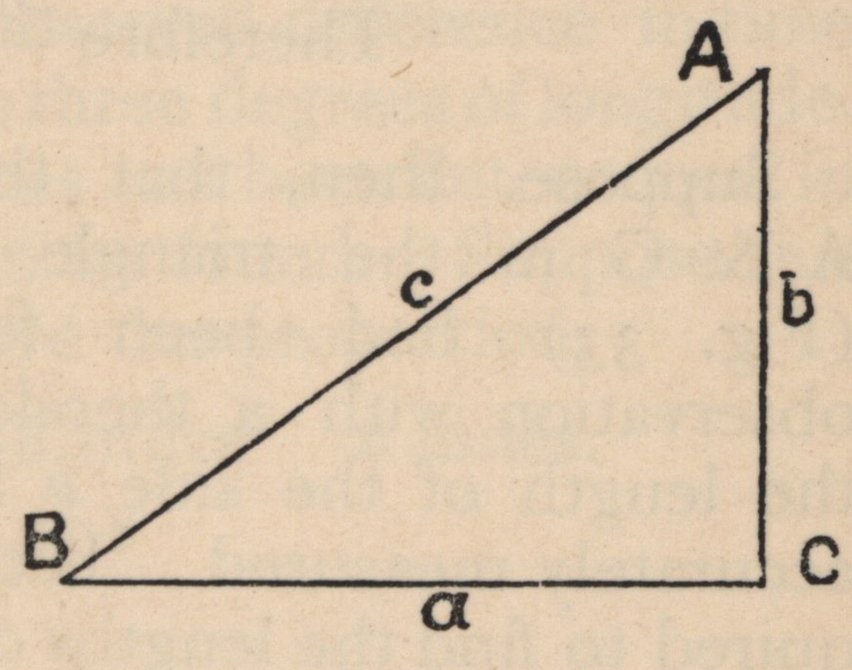


Fig. 32.
Illustrating Trigonometrical Ratios.

The following ratios then exist :—

The *sine* of the angle A B C is $\frac{b}{c}$. the *cosine* $\frac{a}{c}$.

The *tangent* „ „ $\frac{b}{a}$, the *cotangent* $\frac{a}{b}$.

The *secant* „ „ $\frac{c}{a}$, the *cosecant* $\frac{c}{b}$.

They are abbreviated to sin, cos, tan, cotan, sec, cosec.

The ratios hold good for any triangle having the angle at C a right angle.

Solution of Triangles.—Now the dimensions of any triangle can be calculated if the facts known about it fall into one of the four following cases :—

(1.) If the lengths of the three sides are known.
(2.) If two angles and one side are known.
(3.) If two sides and the angle between them are known.
(4.) If two sides and an angle opposite one of them are known.

Given a triangle of which one of these sets of measures has been found by observation, and the remaining angles and sides can be precisely determined by the use of a trigonometrical formula. We shall frequently have occasion to use the second case, in which two angles and a side are the data from which the triangle has to be solved.

Sides and Sines.—The sides and angles of any triangle are directly proportional to each other.

$$\text{Sin A} : \text{Sin B} : \text{Sin C} :: a : b : c,$$

$$\text{Therefore } \frac{\text{Sin A}}{a} = \frac{\text{Sin B}}{b} = \frac{\text{Sin C}}{c}.$$

Suppose, then, that the angles A & C in the triangle A B C (Fig. 33) had been found by observation with a theodolite, and the length of the side *b* had been accurately measured. Let it be required to find the lengths of *a* and *c*. The three angles of any plane triangle make up 180°, so if two of the angles are known, the third can be found by subtracting their sum from 180°. In this case, therefore, B = 180° − (A + C). Now to find *a*. We have $\frac{a}{b} = \frac{\sin A}{\sin B}$,

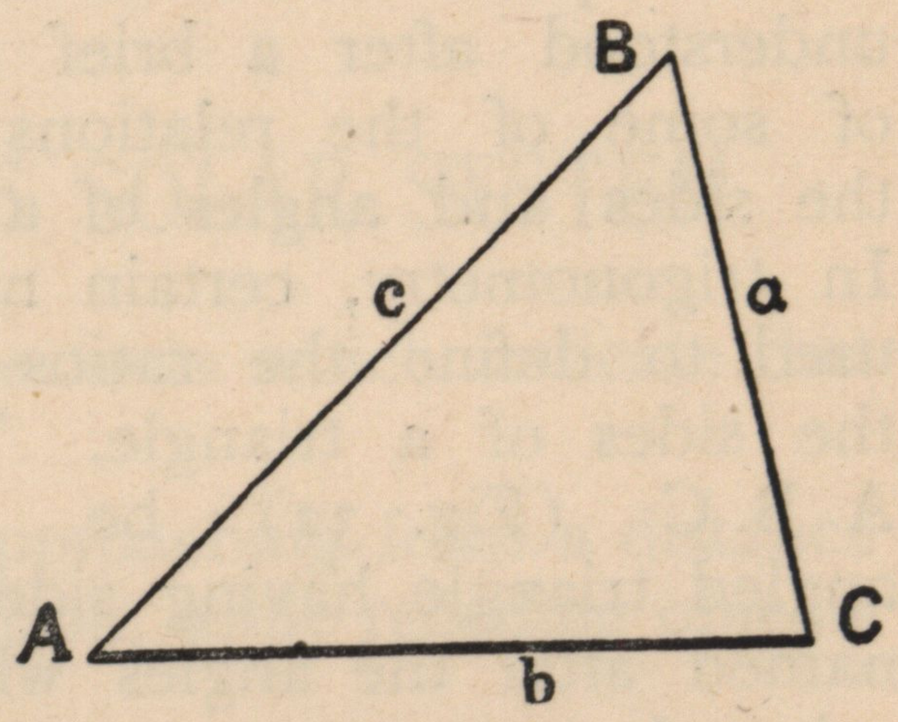


Fig. 33.

Illustrating the relation between the sides and angles of a triangle.

$$\text{Therefore } a = \frac{\text{Sin A} \times b}{\text{Sin B}},$$

$$\text{Similarly } \frac{c}{b} = \frac{\text{Sin C}}{\text{Sin B}},$$

$$\text{And therefore } c = \frac{\text{Sin C} \times b}{\text{Sin B}}.$$

The numerical values of the sines of angles are given in tables, hence, to solve a triangle such as that in the example, it is only necessary to look up these values, and use them in the manner indicated.

Arcs of Latitude and Longitude.—A great circle is the boundary line of that section of a sphere which divides it into two equal parts. All other circles on a sphere are small circles. Meridians of longitude are all great circles; the equator is also a great circle, but other parallels of latitude are small circles. From the preceding illustration of the relation between arcs and angles, it will be manifest that the size of the earth can be found if we know the length of an arc on the equator or along any meridian. These arcs are called respectively 'arcs of parallel' and 'arcs of meridian.'

Arcs of Parallel.—Consider two places at the equator. Then any star comes on the meridian of an observer at the western place later than at the eastern. The interval between the two transits can be accurately found by putting the two places in telegraphic communication. Let the observed difference in time be twelve minutes. This is equivalent to three degrees of longitude. When the distance between the two places has been determined in miles, the circumference of the earth can be found. Suppose this distance to be 198 miles. Then we have the proportion,

$$3 \text{ degrees} : 360 \text{ degrees} :: 198 \text{ miles} : x \text{ miles.}$$

$$\text{Whence } x = \frac{360 \times 198}{3}$$

$$= 23{,}760 \text{ miles.}$$

The distance round the earth along any other parallel of latitude can be determined in a similar manner, and from such observations the true size and shape of the earth can be found. The method generally adopted, however, is the measurement of the length of an arc along a meridian, and not an arc of parallel.

Arcs of Meridian.—The determination of the length of an arc of meridian involves operations which can be summed up as follows:—

(1.) The length of a base-line must be accurately measured, and from it the size of as large a tract as possible, in a north and south direction, determined by triangulation. This is *geodetic* work.

(2.) The distance between two points in the same north and south line, that is, on the same meridian, must be estimated from the geodetic observations.

(3.) The difference of latitude between the selected points must be found. This is the *astronomical* work. The length of a degree of latitude is equal to the distance between the observing stations, divided by the difference of latitude, and by multiplying this by 360, the length of the earth's circumference is obtained.

Measurement of a Base Line.—We will deal with these operations seriatim. It is necessary that the length of the base line should be measured with extreme accuracy. In ordinary land surveying, an iron or steel chain 66 feet long is used to measure the line, but the error which it involves, though unim-

portant when only a small area is measured, is much too large when the size of a country has to be found. General Roy used deal rods for the first base measured in England in 1784, but they were found to change in length from the effects of moisture, so glass rods were substituted. In each case, however, corrections have to be applied for the variation in length of the rods or chain at different temperatures. Major-General Colby, in 1827, invented a contrivance, known as 'Colby's bars,' in which compound bars were arranged to compensate changes of temperature. The principle of the contrivance will be understood from Fig. 34. Let *aa*, *bb*, be two bars of brass and iron respectively, joined by a steel cylinder, *st*, and free to expand at the ends. Flat steel tongues, represented by the lines *ac*, *ac*, move freely on pivots riveted into the bars. On the upper surface of each tongue is inserted a silver pin, with a small dot upon it, indicated by *cc*. The problem is to maintain a constant distance between these points. Suppose an increase of temperature caused *aa* to lengthen to *a'a'*. Then if the brass bar alone expanded, the distance between the two compensation points would be diminished as shown in figure B. But the iron bar also increases in length, though not so much as the brass one, and the arrangement is such that the increase of this bar increases the distance between *cc* by exactly the amount that the distance is decreased by the expansion of the brass bar. The effect of a diminution of temperature is compensated in the same way. The distances of the point *c* from the bars is determined by the proportion :—

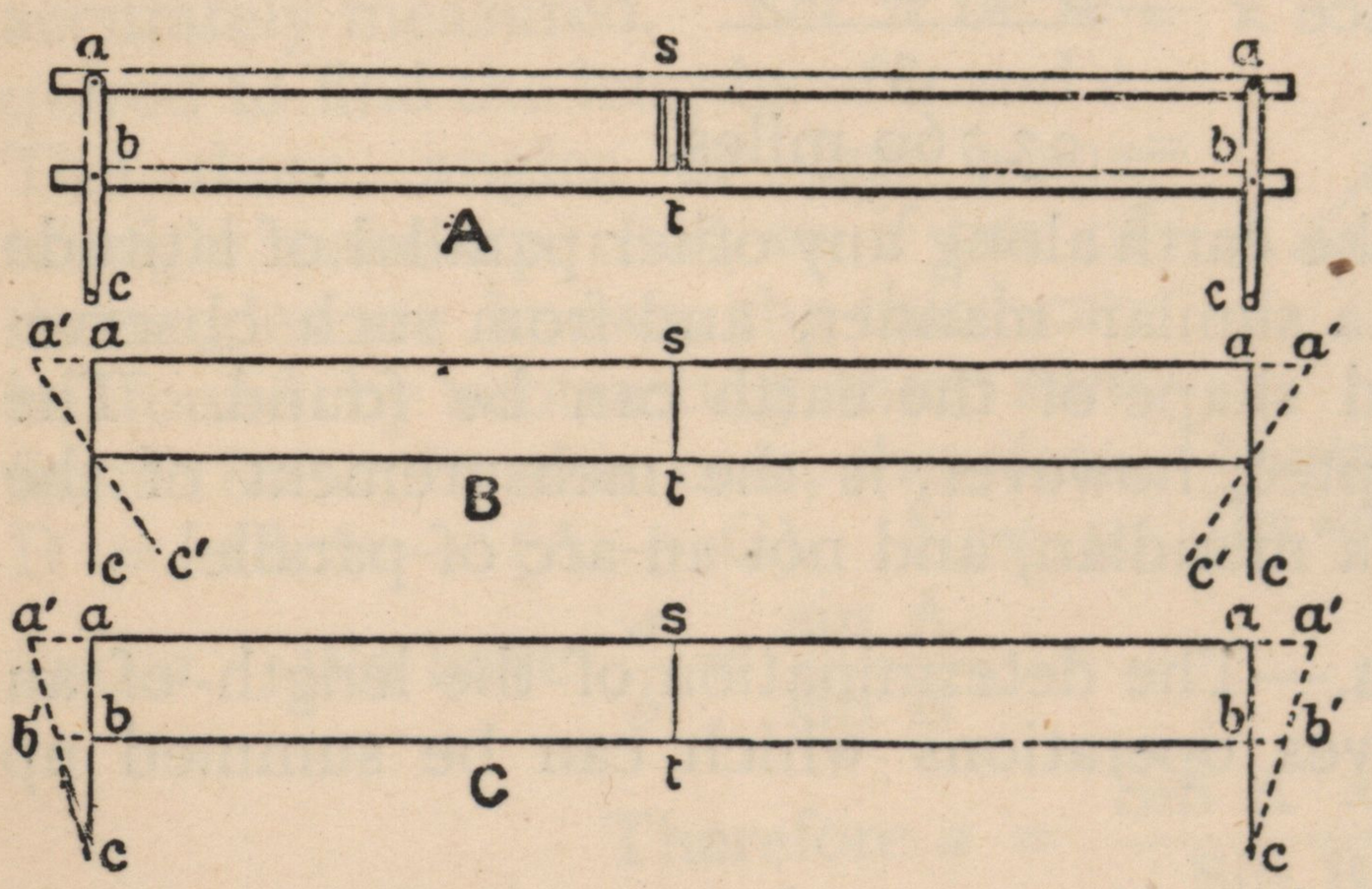


Fig. 34. A shows a plan of Colby's bars ; B, the effect of *a a* expanding alone ; and C, the effect of *b b* expanding with it.

$$aa' : bb' :: ac : bc$$

That is	Expansion of brass bar	:	Expansion of iron bar	::	Distance of the point *c* from the brass bar	:	Distance of the point *c* from the iron bar.

Brass and iron have different capacities for heat, and their surfaces present different powers of radiation and absorption, so the same amount of heat produces different variations of temperature in them. As it is essential that Colby's compensating bars should be at the same temperature, the surfaces of the bars were varnished until experiment showed that each of the two increased or decreased in temperature by the same amount when similarly exposed.

A further improvement in the measurement of a base-line was devised by Colby, viz., the compensating microscope. Two short microscopes were connected together on the same principle as the measuring bars, so that their ends were always at the same distance apart. In measuring the base-line the bars were not placed in contact, but one of the microscopes was sighted upon one of the dots at the extremity of a bar, whilst the dot at the extremity of the next bar was brought into the centre of the field of the other microscope. After a compound bar has had its junction with the following one optically observed, it is removed to the other end of the row and the operation repeated, six bars only being used in measurement of the English base-lines.

It must not be supposed that a perfectly level plain is necessary for the measurement of a base-line by these means. Each compound bar is supported by strong brass tripods resting on trestles, varying in height from six to thirty inches. If the ground differed in level, trestles of different heights were used to support the bar, and then accurately adjusted until a spirit level indicated that the bar was horizontal. By this means the length of a horizontal line was obtained on Salisbury Plain, though there is a difference of level of 428 feet between ground at the two extremities. The compensation bars employed in this determination were six in number, each ten feet long, and were optically connected by means of microscopes six inches apart. The length of the base measured by this means in 1849 was 36,577·07 feet. Major-General Mudge, in 1794, obtained a length of 36,574·23 feet for the same line, using a steel chain to measure it. The difference is 2·84 feet. Not much, certainly, but sufficient to produce a difference of nearly 300 feet in the length of a line joining the Shetland Islands to the Isle of Wight.

Triangulation.—After the base-line has been measured, the size of a tract of country can be found by ordinary land surveying methods. Good theodolites are used for these observations. The surveyor goes to one extremity of the line and directs the telescope

of a theodolite—an instrument for measuring angles—to some distant object, such as a church spire. The instrument is next carried to the other extremity, and again directed to the same object. Each of these two directions makes a certain angle with the direction of the base-line. Knowing the two angles from observation, and the length of the base by measurement, the distance of the church spire from either extremity can be calculated. The calculated distance can then be used as a second base-line, and the distance of another object found by taking sights at it from the two extremities, and so on for any number of times. When the size of a large tract of country has been thus determined, the work of the surveyor is finished.

The following practical remarks by Captain Yolland, R.E., are of importance :—'The best conditioned triangles are those which approach most nearly to the equilateral form, and especial care should be taken to avoid the use of very acute angles, as small errors in the measurement or observation of such angles will produce large errors in the lengths of the sides obtained from them. When the determination of the figure of the earth by means of the measurement of an arc of meridian or of parallel, or when the topography of a large extent of country is the object of the survey, the relative angular bearings of the surrounding stations should be ascertained with the utmost practicable precision; and as the probable error of a distance deduced from any base through a series of triangles increases with the number of intervening steps, the larger the size of the triangles used the better; so that in hilly or mountainous countries the magnitude of the triangles need only be limited by the distance at which, on account of the curvature of the earth's surface, the hazy state of the atmosphere, or the magnifying power of the telescopes of the instruments employed, the objects cease to be visible from each other. Thus in the triangulation of the United Kingdom of Great Britain and Ireland, the largest triangle is that contained by the stations on Snowdon in Wales, approximate altitude 3,575 feet; Sca Fell, in Cumberland, 3,163 feet; and Slieve Donard, one of the Mourne mountains in Ireland, 2,796 feet; the lengths of the sides of which are respectively as follows :—

Snowdon to Sca Fell	...	...	102 miles.
Snowdon to Slieve Donard	...	...	108 „
Sca Fell to Slieve Donard	...	...	111 „

Determination of Latitude.—Having found the area of a large tract of country by geodetical observations, the distance between two points on the same meridian of longitude can be determined, and this being done, the difference of latitude between the two points must be observed. Astronomical measurements are therefore required. The latitude of any place is equal to the angular distance of a star from the celestial equator *plus* its angular distance from the zenith. In Fig. 35 let P represent a place in latitude λ, Z, the zenith of the place, and S, any star. We have, therefore :—

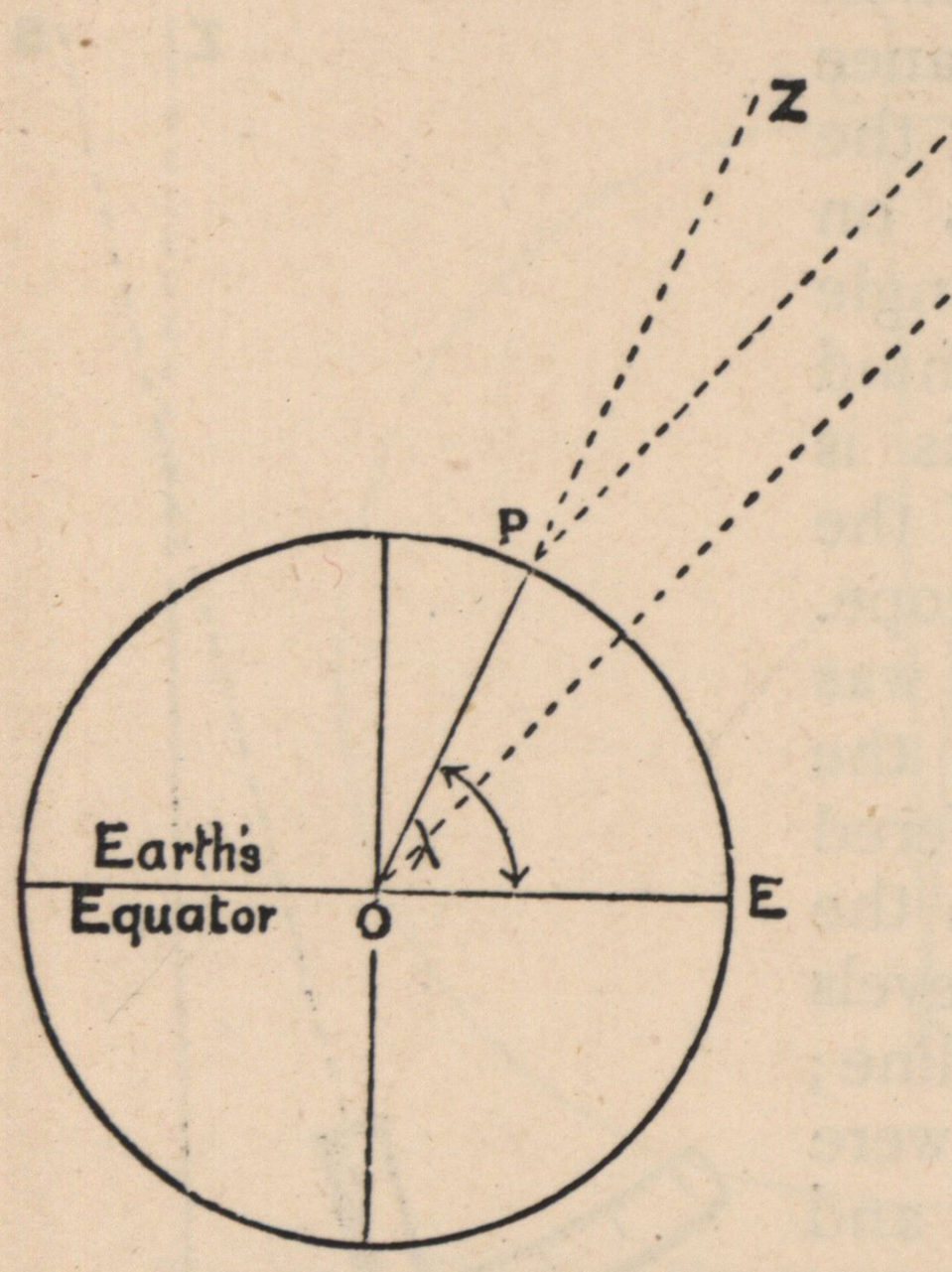


Fig. 35. To show that latitude equals declination *plus* zenith distance.

Zenith distance of star S = the angle Z P S
Declination „ „ = „ „ E O S
Latitude of place P = „ „ E O Z

Then E O Z = E O S + S O Z

But S P, S O are parallel,

Therefore E O Z = E O S + Z P S,

That is, Latitude = Declination + Zenith Distance.

Catalogues are prepared in which the declinations of stars are given to fractions of a second of arc. Hence, the only operation required in the determination of latitude by the above-described method is to find the zenith distance of a star of known declination. This is done by means of a zenith sector.

The Zenith Sector.— By means of this instrument the positions of stars near the zenith, where the effect of atmospheric refraction is least, can be very accurately determined. A zenith sector in its simplest form consists of a radiating metal arm, having a graduated arc and a telescope attached to the lower end. The arm is suspended from the upper end, and from the centre of motion a plumb-line hangs so as to be very near the graduated

arc. The direction of the plumb-line determines the position of the zenith. If the telescope is directed to a star in the zenith its axis will coincide with the direction of the plumb-line. The zenith distance of any star is found by directing the telescope to the star when it is on the meridian, and observing the angle on the graduated arc directly behind the plumb-line. (Fig. 36.) This is the angle between the direction of the plumb-line and that of the telescope. A new kind of zenith sector was devised by Sir George Airy for the English Ordnance Survey. It differed from the old form of instrument in the following respects—(1) Spirit-levels were substituted for the plumb-line; (2) as many parts as possible were cast into one piece, the telescope and the microscope for reading the graduated arc being part of the same solid frame.

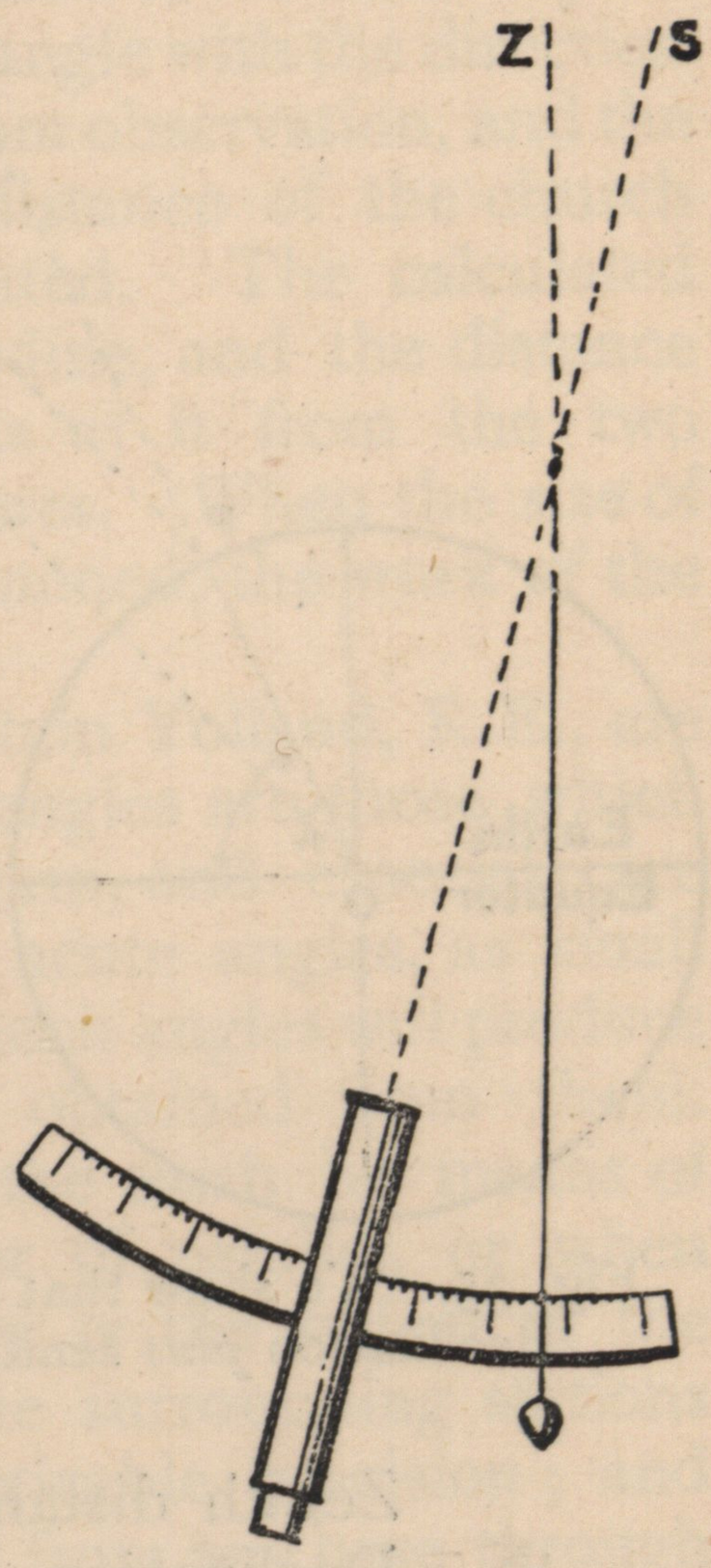


Fig. 36. Principle of the Zenith Sector.

The Form of the Earth.—The earth has the form of an oblate spheroid. An indication that this is the case is afforded by the fact that degrees of latitude increase in length in passing from the equator to the poles. At the equator a distance of 68·69 miles must be travelled in a north and south direction in order to pass over a degree of latitude; at the poles the requisite distance is 69·39. The difference is nearly three-quarters of a mile. That the conclusion drawn from this difference is a correct one will be understood from Fig. 37. Let A C and B C represent the directions of two plumb-lines on a meridian near the equator, and let the angle A C B, which is the difference of latitude between A and B, be one degree. Similarly let D E represent the distance which it is necessary to travel near the poles, in order to produce an angle of one degree between the two directions D F, E F; that is, in order to pass over one degree of latitude. Observations show that the distance A B is less than D E. The curvature of the earth's surface is therefore more rapid than at D E, or, in other words, the earth is flatter near the poles than near the

equator. The difference of length between the polar and equatorial diameters is about 26 miles, or $\frac{1}{294}$ of the equatorial

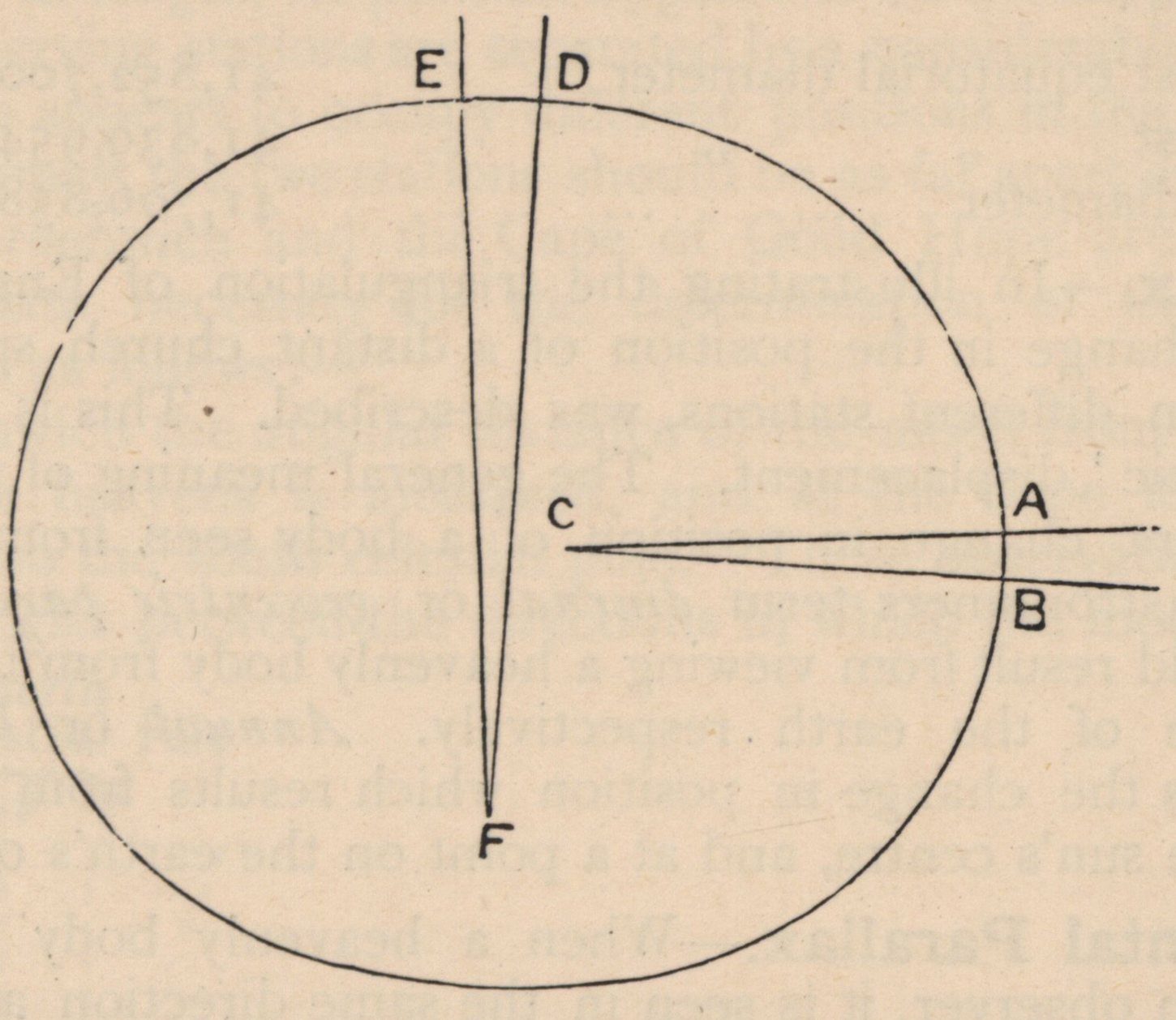


Fig. 37. Showing the cause of the difference in length of Degrees of Latitude.

diameter. The fraction is termed the earth's oblateness or ellipticity.

The Earth's Oblateness.—The ellipticity or oblateness of the earth can also be found by observations of the variation of gravity, as indicated by pendulum observations. A pendulum which beats seconds at the equator has its rate increased in passing from the equator towards the poles. One method of observation is to vary the length of the pendulum so that the interval between two consecutive beats shall be the same at each place. Another method is to keep the length of the pendulum invariable and find the increase in the rate of vibration in different latitudes. The ratio of the centrifugal force at the equator to the force of gravity at the equator is as 1 : 289. Calling this ratio f, and the force of gravity g, it can be shown that the ellipticity (e) of the earth is given by the expression :—

$$e = \frac{5f}{2} - g.$$

If the earth is imagined to be cut in half through the equator, the section obtained would not be circular but slightly elliptical. It is found that the longest equatorial diameter passes through

the meridian 15° 34′ E. of Greenwich, and the shortest equatorial diameter passes through the meridian 105° 34′ E. The values obtained are :—

Longest equatorial diameter	...		...	41,852,700 feet.
Shortest „	„		...	41,839,954 „
Polar diameter	...	...	...	41,706,858 „

Parallax.—In illustrating the triangulation of England, the apparent change in the position of a distant church spire, when viewed from different stations, was described. This is known as a 'parallactic' displacement. The general meaning of parallax is the apparent change in position of a body seen from different places. Astronomers term *diurnal* or *geocentric parallax* that which would result from viewing a heavenly body from the surface and centre of the earth respectively. *Annual* or *heliocentric parallax* is the change in position which results from viewing a body at the sun's centre, and at a point on the earth's orbit.

Horizontal Parallax.—When a heavenly body is in the zenith of an observer, it is seen in the same direction as it would be if viewed from the earth's centre, and has, therefore, no parallax ; but when the body is on the horizon, the observer, and an imaginary eye at the earth's centre, see it from the extremities of the earth's radius, and the parallax is greatest. This is termed the horizontal parallax. The difference will be understood from Fig. 38, in which a celestial body is viewed by an observer at D in the positions B, A, R, and L, that is, in the zenith, on the horizon, and at two intermediate points. The angle which a line joining the observer to the earth's centre subtends at the object is seen to be greatest when the object is on the horizon.

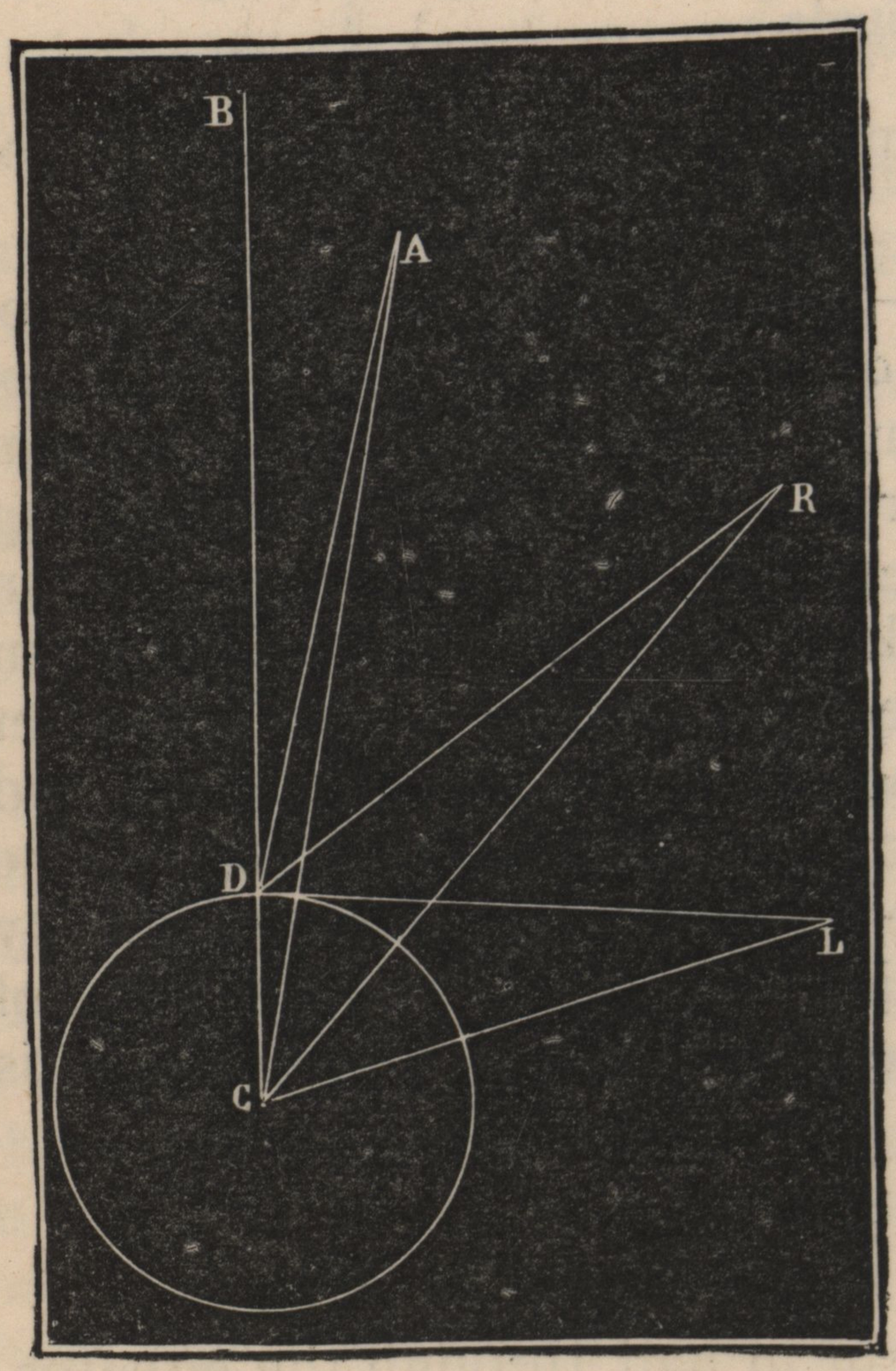


Fig. 38.
Illustrating Horizontal Parallax.

Measurement of the Distance of the Moon.—When the moon is simultaneously observed from the extremities of a line a few miles in length, its position appears to be the same. But if the two observing stations are separated by a considerable distance, our satellite appears to occupy different positions in the sky. To ensure accuracy, the two stations should be as far apart as possible. Suppose Greenwich and the Cape of Good Hope are selected, then the data necessary for the determination of the moon's distance are as follows:—

At Greenwich the angular distance of the moon from the north pole of the heavens is measured, and at the Cape its angular distance from the south celestial pole. These observations determine the angles between the directions in which the moon is seen

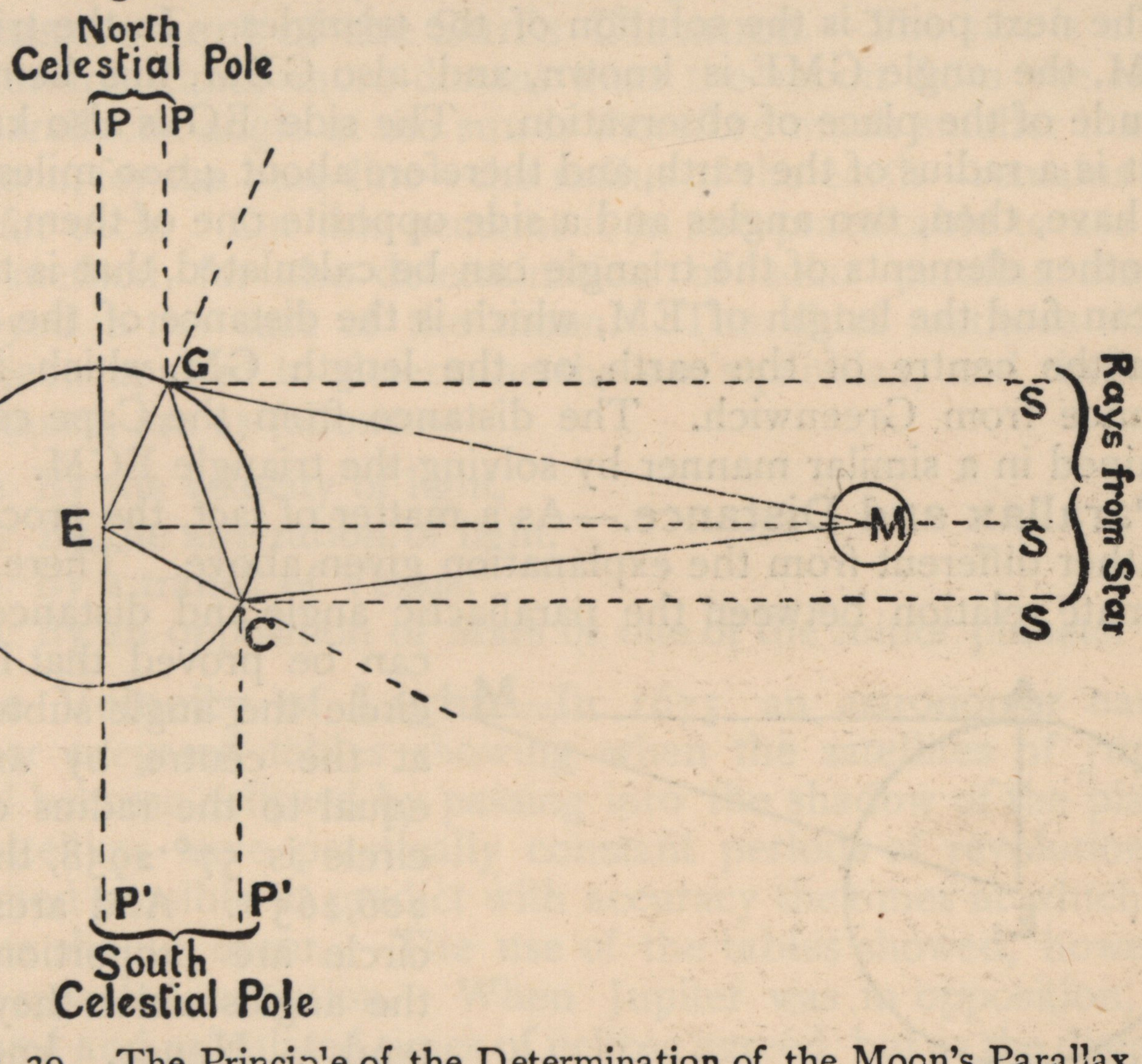


Fig. 39. The Principle of the Determination of the Moon's Parallax.

and the line joining the two stations. If the moon were infinitely distant from the earth we should have north polar distance *plus* south polar distance equals 180°. The sum of the observed polar distances is greater than 180° by the angle which the line joining the two stations subtends at the moon. For the stations selected the angle is about $1\frac{1}{2}°$.

This is the 'parallactic angle,' and from it the distance of the moon from either of the observing stations, or from the centre of the earth can be calculated by trigonometry.

The method is illustrated by Fig. 39, in which E and M are the centres of the earth and moon, G and C represent the observatories at Greenwich and the Cape, S, a star, PP′ the north and south celestial poles, or points directly above the ends of earth's axis, ZZ′ the zeniths at the places of observation. The angles measured are PGM and P′CM, and SGM + SCM represent the angle by which the observed polar distances exceed 180°.

Now since SG and SE are parallel, EMG is equal to SGM. Similarly EMC is equal to SCM. Therefore SGM + SCM = CMG, the 'parallactic' angle subtended by the line CG.

The next point is the solution of the triangles. In the triangle GEM, the angle GME is known, and also GEM, this being the latitude of the place of observation. The side EG is also known, for it is a radius of the earth, and therefore about 4,000 miles long. We have, then, two angles and a side opposite one of them, so all the other elements of the triangle can be calculated, that is to say, we can find the length of EM, which is the distance of the moon from the centre of the earth, or the length GM, which is her distance from Greenwich. The distance from the Cape can be obtained in a similar manner by solving the triangle ECM.

Parallax and Distance.—As a matter of fact, the procedure is rather different from the explanation given above. There is an intimate relation between the parallactic angle and distance. It can be proved that in any circle the angle subtended at the centre by an arc equal to the radius of the circle is 57°·2958, that is, 206,265″. And arcs of a circle are proportional to the angles which they subtend. Hence, knowing that the chord GC subtends an angle of $1\frac{1}{2}°$, the angle which it would subtend if its length were that of an equatorial radius of the earth can be found by proportion. This angle is known as the moon's equatorial horizontal parallax, and its value is 3,422″, that is, 57′ 2″. To find the moon's distance from its parallax, let EA

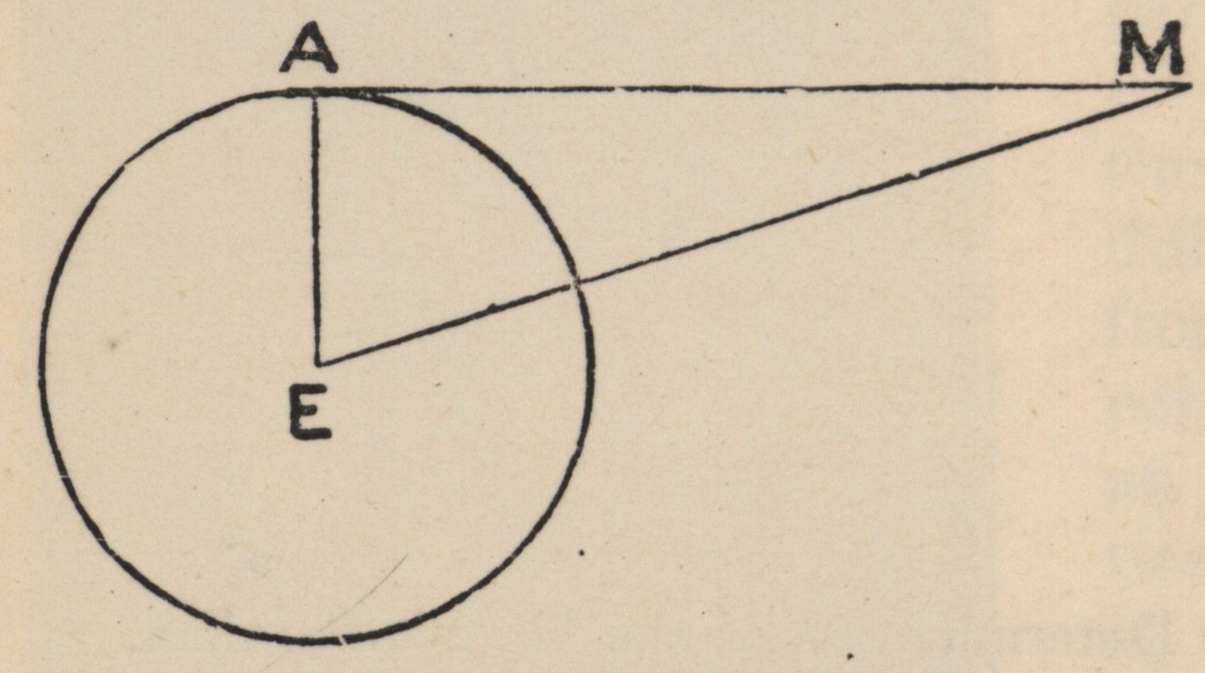


Fig. 40. Illustrating the relation between Parallax and Distance.

in Fig. 40 represent a radius of the earth (3960 miles), M, the moon, and AME, the moon's equatorial horizontal parallax.

Then 3,422 : 206,265 :: 3960 : x.

Whence $x = \frac{206{,}265 \times 3960}{3422}$ = 239,000 miles (about).

Expressing the same thing by trigonometry we have

$$\text{Distance of moon (EM)} = \frac{\text{EA}}{\sin \text{EMA}}$$

$$= \frac{\text{Equatorial radius of earth}}{\sin 57' 2''}$$

= 239,000 miles (about).

Measurement of the Sun's Distance.—The sun is nearly four hundred times more distant than the moon from the earth. The parallactic angle at the sun is therefore much smaller than at the moon, for the base line—the radius of the earth—remains the same for each. On this account it is not practicable to use the same method for the determination of solar parallax that is employed in the case of the moon. The chief methods which have been applied to determine the sun's parallax, and therefore its distance, are as follows:—

(1.) By the velocity of light.
(2.) By the aberration of light.
(3.) By a transit of Venus.
(4.) By an opposition of Mars or one of the minor planets.

The Velocity of Light.—In 1675, an astronomer named Roemer prepared tables showing when the satellites of Jupiter should become eclipsed by passing into the shadow of the planet. The satellites have practically constant periods of revolution, so it seemed possible to predict with accuracy the times at which the eclipses should occur. The use of the tables showed, however, an unexpected variation. When Jupiter was in opposition, the observed and calculated times of eclipse agreed, but as the distance between the planet and the earth increased, the eclipses gradually occurred later than they should have done according to the tables, until when Jupiter was in conjunction, the retardation was nearly 1,000 seconds for each of the satellites. From conjunction this difference was gradually diminished, and became *nil* when the planet was again in opposition. It appears, therefore, that the variation is connected in some way with the synodic revolution

of Jupiter, and the idea at once suggested itself to Roemer that the 1,000 seconds (16m. 40s.) represented the time required by light to travel across the earth's orbit (Fig. 41). This afterwards proved to be the case. Hence, the distance of the sun being taken as 93,000,000 miles, it is possible to determine the velocity

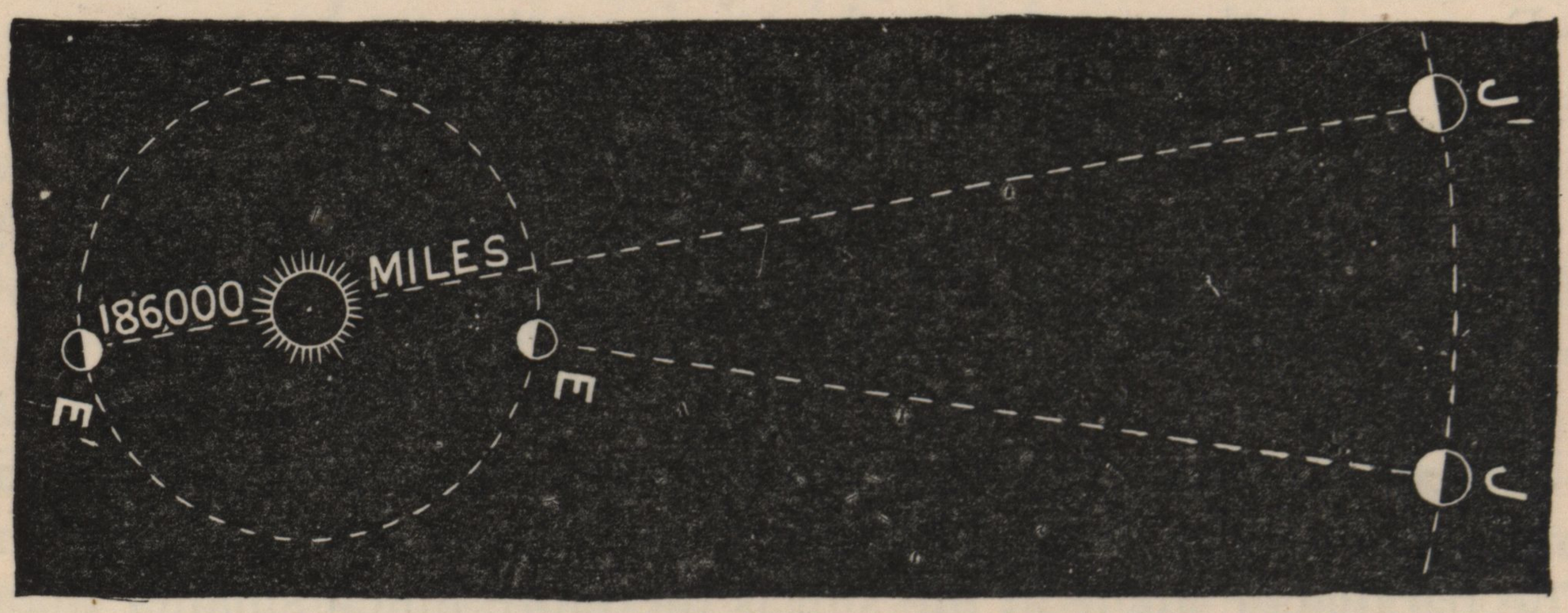


Fig. 41. Determination of the Velocity of Light, by observations of Jupiter's Satellites.

of light by observations of the times of eclipses of Jupiter's satellites. For if light takes 1,000 seconds to travel twice 93,000,000 miles, that is, 186,000,000 miles, then in one second it travels 186,000 miles. To be accurate, the time required by light to pass from the sun to the earth is 499 seconds. It is known as the Light-equation constant.

Distances of Sun determined by the Velocity of Light.—By assuming the sun's distance, the velocity of light has been obtained from the light-equation, as explained above. The process can be reversed. If we know the velocity of light, the distance of the sun can be determined. In recent years, several investigators have found from laboratory experiments that the rate at which light travels is about 186,400 miles per second. But light takes 499 seconds to travel from the sun to the earth. The distance of the sun is therefore 186,400 × 499 miles, that is, about 93,000,000 miles.

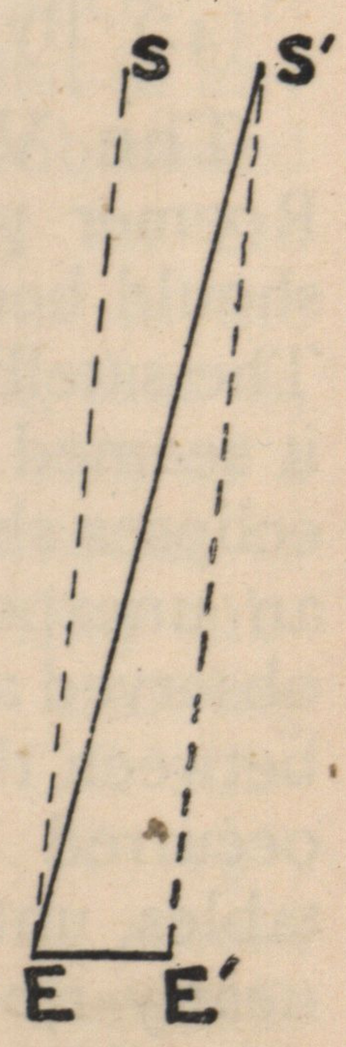


Fig. 42.
Angle of Aberration SES'.

Constant of Aberration.—If, in Fig. 42, SE represent the direction in which a star would be seen if the earth were at rest, and S'E the direction in which it is seen on account of aberration,

the angle SES′ is the 'constant of aberration.' SE is parallel to S′E′, hence SES′ is equal to ES′E′. And if we suppose the earth to move through EE′ while light travels from S′ to E′, we get the trigonometrical ratio :—

$$\frac{EE'}{E'S'} = \tan ES'E'.$$

Therefore $EE' = E'S' \times \tan ES'E'$

That is, velocity of earth = velocity of light × tan of aberration constant.

Sun's Distances determined by Aberration Constant.—The orbital velocity of the earth having been obtained in the manner described in the preceding paragraph, and the velocity of light having been found by laboratory experiments, it is possible to determine the sun's distance. Thus, the mean orbital velocity is 18·5 miles per second. The number of miles traversed in a sidereal year (35,558,149 seconds), that is, the circumference of the earth's orbit, is 35,558,149 × 18·5, that is, 583,825,756 miles. By dividing this number by $2 \times 3\frac{1}{7}$, the radius of the orbit, or in other words, the sun's distance, is found to be about 93,000,000 miles.

The problem can also be expressed as follows :—

Let V represent the velocity of light, *a* the constant of aberration, *n* the earth's mean orbital velocity, and *e* the eccentricity of the orbit, then the time (T) taken by light to travel from the sun to the earth is given by the equation :—

$$T = \frac{a\sqrt{1 - e^2}}{n}$$

Multiplying this by V, we get the sun's distance (D) thus :—

$$D = \frac{aV\sqrt{1 - e^2}}{n}$$

Relative Distances of Planets.—The relative distances of the planets from the sun were known long before the absolute distance of any one of them was obtained. As soon as a correct determination of the distance of the earth had been made, therefore, it became possible to substitute absolute distances for the previous relative ones. Conversely, the distance of a planet from the sun having been correctly estimated, the span of space between ourselves and our luminary can be calculated. Fig. 43 gives an idea of a method which has been employed to obtain relative

distances. In this illustration, S represents the Sun; E, the Earth; V, Venus; and M, Mars, while the circles round the sun indicate the orbits of these planets. If, when Venus and the earth occupy

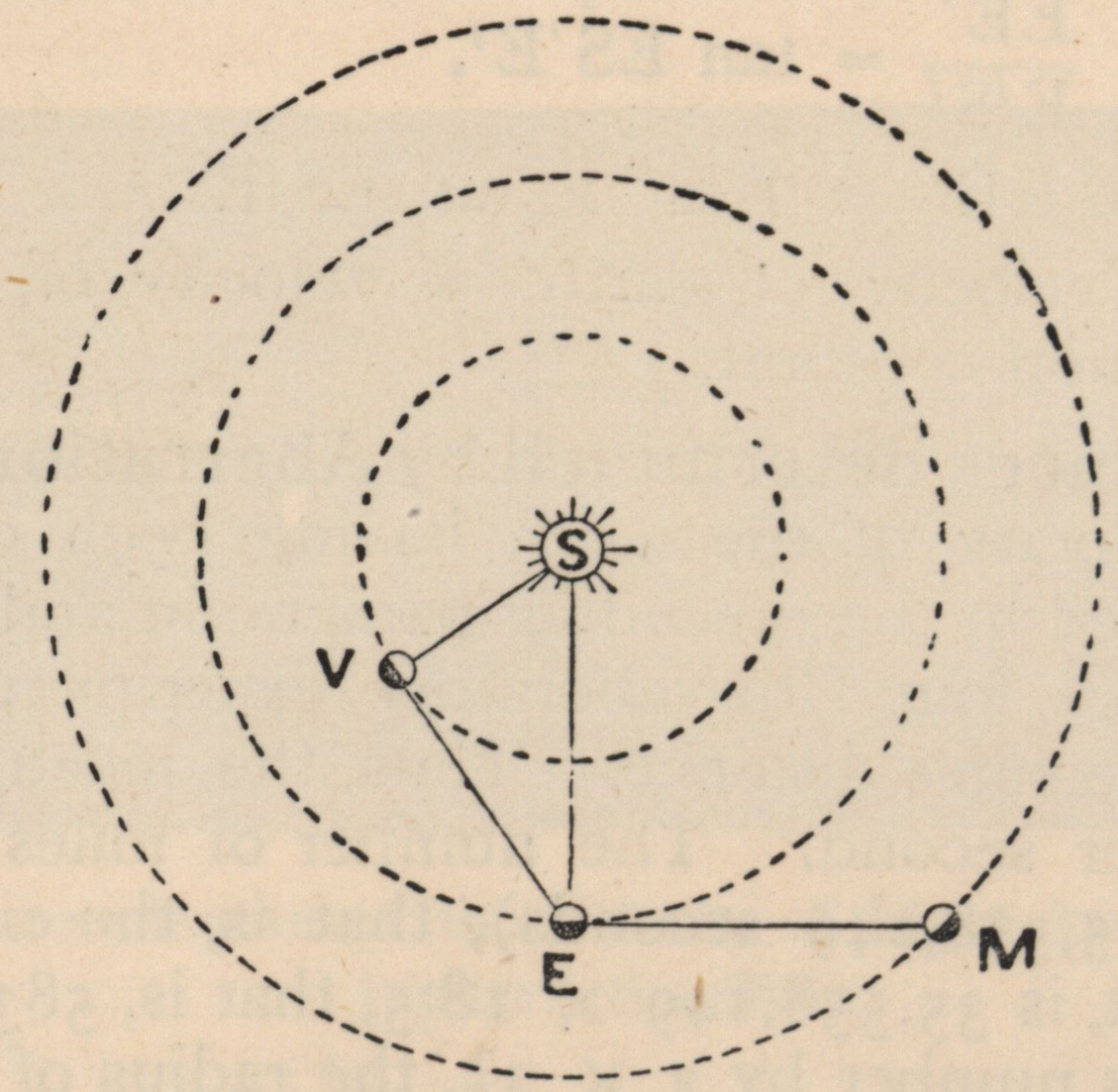


Fig. 43. Old method of determining the relative distances of Venus and Mars from the sun.

the relative positions shown, the angular distance of the former planet from the sun (the angle V E S) is measured, we get the proportion :—

$$\text{Distance of Venus} : \text{Distance of Earth} :: \text{V S} : \text{E S}$$

$$\text{Therefore} \quad \frac{\text{Distance of Venus}}{\text{Distance of Earth}} = \frac{\text{V S}}{\text{E S}} = \text{Sin V E S}$$

The angle V E S is 47°, and the sine of this is 0·72. Hence, if 1 represent the earth's distance, 0·72 represents the distance of Venus, while the distance of the planet from the earth is 1 — 0·72, that is 0·28. In like manner the relative distances of the earth and a superior planet can be found, for we again get the proportion :—

$$\text{Distance of Planet} : \text{Distance of Earth} :: \text{E S} : \text{M S},$$

$$\text{Therefore} \quad \frac{\text{Distance of Planet}}{\text{Distance of Earth}} :: \frac{\text{E S}}{\text{M S}} = \text{Sin E M S}$$

Distance of Mars.—The parallactic angle, or parallax, of Mars is found by measuring the change of position on the dark background of space which the planet undergoes when viewed

from the same observatory at an interval of twelve hours. This is equivalent to observing the planet from the extremities of a base-line 8,000 miles long, if we suppose the observatory to be situated on the equator. Let M in Fig. 44 represent Mars, C an observer on the earth's equator, and S a star. The observer would see Mars projected on the sky at *m*. Twelve hours later the planet would appear on the other side of the star in the position *m'*, for the observer would then be at C'. The angle *m*M*m'* is thus found, and the required angle CMC' is

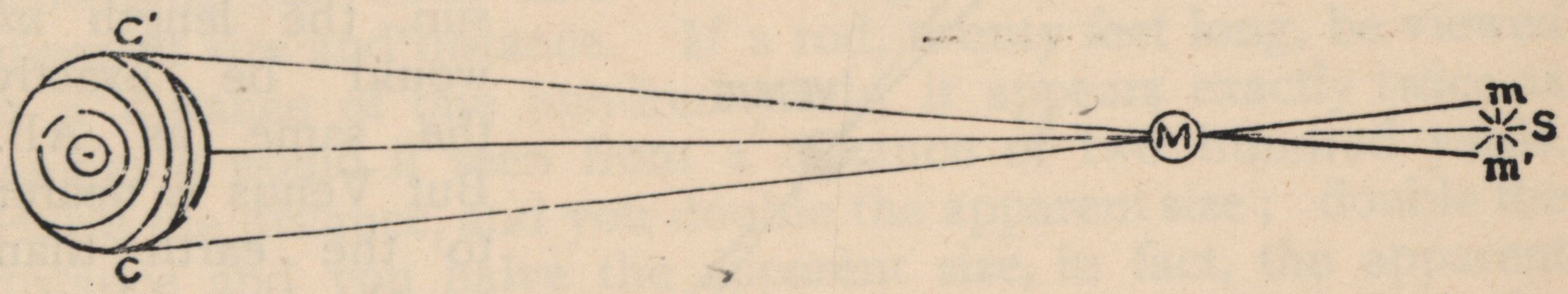


Fig. 44. Illustrating the method of determining the parallax of Mars.

equal to it. Knowing this angle, the distance of the planet from the earth can be calculated as in the case of the moon. The distances of any of the minor planets can be similarly found by observing them at or near opposition. Mars, when in opposition, is about three times farther from the sun than from the earth. Hence, the distance of Mars being found by the above means, its actual distance from the sun, and also the earth's distance from the sun, can be estimated by proportion.

Distance of Venus and the Sun.—The distances of Venus from the earth and sun respectively have been shown to be in the proportion of 28 to 72. The accurate relation between the two is given by Kepler's Third Law (see p. 87). The determination of the distance of the planet in question from the earth thus carries with it a knowledge of the sun's distance from us. When Venus passes between the earth and sun, it is seen as a dark spot travelling across the solar disc. Observations of such 'transits of Venus' enable the solar parallax to be found. The method is briefly as follows:—Two stations are chosen as far apart as possible, one in the northern hemisphere, the other in the southern. The sun acts as a screen, upon which is seen the planet. To observers in the northern hemisphere, Venus appears lower on the sun's disc than to observers in the southern hemisphere. The angle required is that subtended at Venus by the line joining these two points.

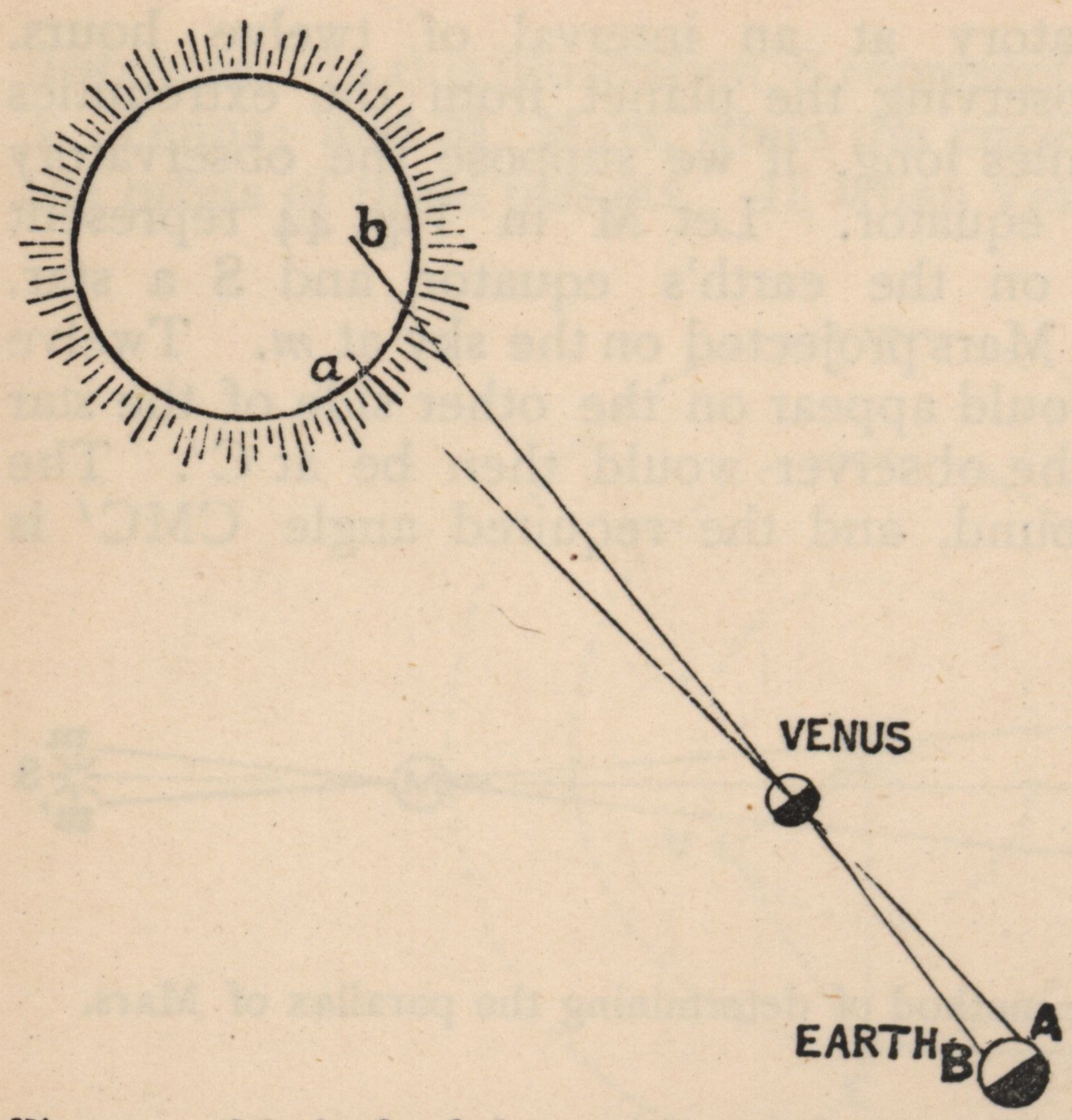


Fig. 45. Method of determining Solar Parallax by observations during a transit of Venus.

In Fig. 45 let *a b* be two points on the sun's disc in which the planet Venus appears to observers A B on the earth. Then it will be evident that if Venus were midway between the earth and sun, the length *ab* would be exactly the same as AB. But Venus is nearer to the earth than to the sun, hence *ab* will be greater than AB. In fact, we get the proportion :—

Venus from Earth : Venus from Sun :: AB : *ab*.

Let A and B represent two stations about 5,260 miles apart, and let the angular separation of *ab* be $30''$ or $\frac{1}{64}$th of the sun's apparent diameter. Then to find the length of *ab* in miles we proceed as follows; accepting the relative distances already given.

$$28 : 72 :: 5260 : ab$$

$$\text{Therefore } ab = \frac{5260 \times 72}{28}$$

$$= 13{,}540 \text{ miles (about)}$$

$$\text{And the sun's diameter} = 13{,}540 \times 64$$

$$= 866{,}500 \text{ miles.}$$

Now the sun's apparent diameter is $32'$; that is to say, 866,500 miles at the distance of the sun subtends an angle of $32'$. Hence, the angle which would be subtended by the earth's equatorial radius at the sun's distance—the solar parallax—is given by the proportion :—

866,500 : 4,000 :: $32'$: Sun's Parallax,

Hence, Sun's Parallax = $8''{\cdot}8$.

There are various practical difficulties which preclude the possibility of measuring directly the angular distance *ab*. What is really done, is to observe the duration of the transit from widely separated stations, and then to deduce the difference in the lengths of the chords traversed. The positions of the chords are thus found, and their angular separation can therefore be calculated.

Determination of the Size of the Sun.—The relation between parallax and distance has previously been noted, and something has been said concerning the connection between apparent size and distance. If a rod, twenty feet long, be viewed at a distance of one hundred yards, it appears exactly twice as long as it would if seen from a distance of two hundred yards. Halve the distance, and you double the apparent size; double the distance and you halve the apparent size, in fact, the apparent sizes of objects are inversely proportional to the distance from the point of observation. To apply this principle to the determination of the size of the sun, moon, or a planet, when their distances are known, we have the proportion :—

$$\text{Distance of object} : \text{Diameter of object} :: \frac{\text{Number of seconds in arc equal to radius}}{\text{Apparent angular diameter}}$$

Thus, the sun's distance is 93,000,000 miles, and its angular diameter is $32'$.

To find its size we have :—

$$93{,}000{,}000 : \text{Diameter of Sun} :: 206{,}265'' : 1920''.$$

$$\text{Therefore, Diameter of Sun} = \frac{93{,}000{,}000 \times 1{,}920}{206{,}265}$$

$$= 866{,}000 \text{ miles.}$$

To find the sun's surface, the square of the radius must be multiplied by $4 \times 3\frac{1}{7}$.

Determination of the Sizes of Planets.—When the distances of planets are known, and their angular diameters have been measured, the sizes can be calculated in the manner shown in the preceding paragraph. The apparent angular diameters of the planets vary very considerably on account of the variable distances of those bodies from the earth. The following table exhibits the angular and real diameters of the chief planets.

Name.	Apparent Angular Diameter.	Real Diameter.
Mercury	5″—13″	3,030
Venus	11″—67″	7,700
Mars	4″—25″	4,200
Jupiter	32″—50″	86,500
Saturn	14″—20″	73,000
Uranus	3″·9	32,000
Neptune	2″·8	35,000

Sizes of Satellites.—The diameters of satellites cannot usually be determined without a large percentage of error. The sizes of Jupiter's satellites are the best known. Jupiter's fourth satellite is the largest of all, its diameter being 3,550 miles. Saturn's fifth satellite has a diameter of 3,500 miles. The second satellite of Jupiter, the eighth of Saturn, and the satellite of Neptune have approximately the same diameter as our moon, viz., 2,160 miles. The two satellites of Mars are by far the smallest in the solar system, the diameter of the nearest to the primary being about 8 miles, whilst the other is only 5 miles across.

QUESTIONS ON CHAPTER IV.

1. How is a measured 'base-line' used in determining the length of an arc of meridian? (May, 1890.)
2. How is the length of a degree in a meridional arc measured? (May, 1887.)
3. How have the shape and size of the earth been determined? (May, 1884, 1877.)
4. How has it been proved that the earth is not a perfect sphere? (May, 1878.)
5. How has the distance of the moon been determined? (May, 1886.)
6. What methods have been applied to determine the distance of the sun from the earth? (May, 1891, 1883.)
7. Describe the observations necessary to measure an arc of meridian? December, 1889.)
8. How does a knowledge of the velocity of light enable the sun's distance to be determined?
9. What is meant by the moon's 'horizontal parallax'? Illustrate your answer with a diagram.
10. Describe fully how the distance of the sun is obtained from observations of Mars in opposition.
11. What is the relation between the angular and real diameters of a member of the solar system?
12. The sun's distance is about 93,000,000 miles, and its apparent angular diameter 32′. Deduce from this the sun's real diameter.

CHAPTER V.

MOTION AND MASS.

Laws of Motion.—Newton formulated three axioms or laws which govern the movements of bodies, and Clerk Maxwell states them as follows:—

(1.) Every body perseveres in its state of rest or of moving uniformly in a straight line, except in so far as it is made to change that state by external forces.

(2.) Change of motion is proportional to the impressed force, and takes place in the direction in which the force is impressed.

(3.) Re-action is always equal and opposite to action, that is to say, the actions of two bodies upon each other are always equal and in opposite directions.

The first law asserts that a body cannot move of itself, and that if it is once set in motion it will go on for ever, unless some force prevents it from doing so. From the second law, we see that whatever the number of forces which act on a body, each produces its full effect, and the direction of motion is the resultant of all the actions. The third law shows that there are two ways of looking at every action, for each body can be considered to act upon the other. All action is therefore in the nature of stress.

Velocity, Acceleration, and Time.—Bodies fall on account of the attraction stress between them and the earth. Common experience tells us that a stone let fall from a bridge increases its velocity until it reaches the earth's surface. Scientific observation shows that if a body move from rest towards the earth, then—

At the end of	1	second	its velocity is	32	feet	per	second.
,,	,,	2	seconds	,,	,,	64	,,	,,
,,	,,	3	,,	,,	,,	96	,,	,,
,,	,,	4	,,	,,	,,	128	,,	,,

It will be seen that a velocity of 32 feet per second is superadded to the original velocity during every second of motion. This is known as the 'acceleration due to gravity.' Calling this g, the velocity of the falling body at any instant v, and the number of seconds of motion t, we get the equation—

$$v = gt.$$

Hence, knowing the acceleration of gravity and duration of motion, the velocity of a body can be calculated.

Space, Acceleration, and Time.—The space traversed by a falling body is also connected with acceleration and time. In the case of a body moving from rest under the action of gravity, we have :—

At the beginning of the 1st second the velocity is 0.

" " 4th " " " 96 ft. per sec.

The acceleration may be taken as uniform ; hence the average velocity during the first three seconds is $\frac{96}{2} = 48$ feet per second. If the average velocity of a train is known, the distance which the train would travel in a given time can easily be found. In like manner, the average velocity of a falling body having been found as above, the space traversed can be obtained by multiplying it by the duration of motion.

Let S represent the space traversed ; g the velocity at the end of the first second of motion ; t the duration of motion in seconds. Then the above result is expressed algebraically as follows :—

$$\text{Velocity at beginning} = 0$$
$$\text{" " end} = gt$$
$$\text{Average velocity} = \frac{gt}{2}$$
$$\text{Therefore, space traversed} = \frac{gt}{2} \times t$$
$$\text{That is, } S = \tfrac{1}{2} gt^2.$$

Hence, In 1 second a body travels over 16 feet.

" 2 seconds " " " 64 "

" 3 " " " " 144 "

" 4 " " " " 256 "

Gravitational Stress between the Earth and Moon.—The earth attracts bodies towards its centre, and the effect of the action is termed weight. Whether on the summit of a mountain, or at the heights attained by balloonists, the attraction of the earth is felt. But as the distance from the earth's centre is increased, the force

of attraction diminishes in intensity. Pendulum observations show that the force varies inversely as the square of the distance from the earth's centre. Why should not this rate of diminution exist beyond the regions which are accessible to us? Assuming that it did so, Newton was able to calculate the intensity of the attraction stress at the distance of the moon (240,000 miles). The radius of the earth is about 4,000 miles in length, so a body at the moon's distance is sixty times further removed from the earth's centre than a body on the earth's surface. Consider the body at rest. The attraction of the earth would set it in motion, and during the first second it would move through a distance much less than the sixteen feet, which represents a body's fall in a second at the earth's surface. In fact,

$$\text{The fall per second} = \frac{16}{60^2} = 0{\cdot}0044 \text{ feet.}$$

That is to say, the fall of the body towards the earth is 0·0044 feet in one second.

But the moon is not at rest, it moves round the earth in $27\frac{1}{2}$ days, in an orbit the size of which is determined by the earth's attraction. The fraction 0·0044 feet represents the amount by which the portion of the orbit traversed by the moon in one second differs from a straight line. Imagine a line to be drawn from the centre of the moon to the centre of the earth at the beginning and at the end of a second. Then the angle (x) contained between these two lines is given by the proportion :—

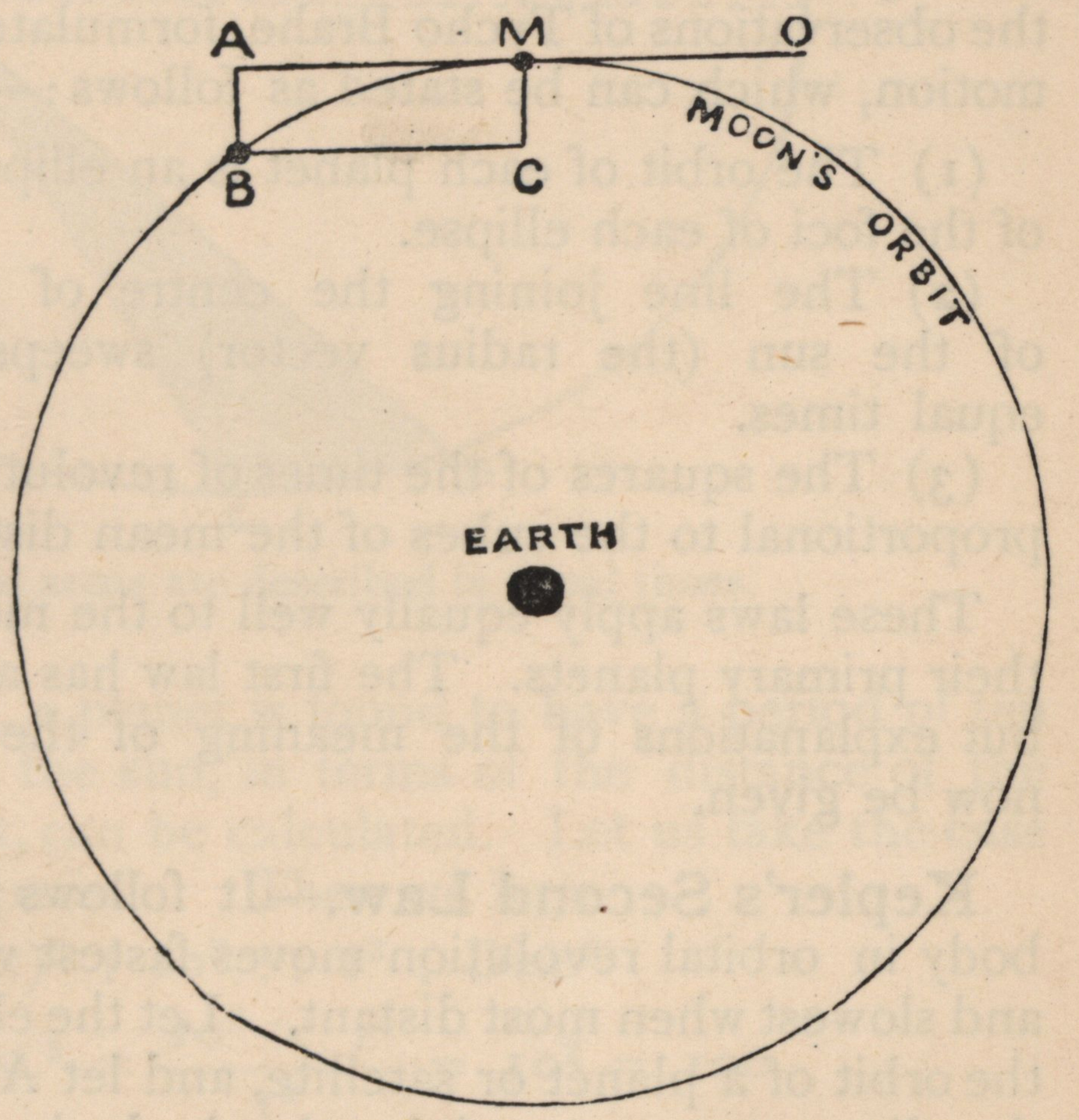


Fig. 46. Illustrating the fall of the Moon towards the Earth.

$$27 \text{ d. } 7 \text{ h. } 43 \text{ m. } 11 \text{ s. : } 1 \text{ s. :: } 360^\circ : x$$

Whence $x = 0''{\cdot}5$.

Fig. 46 illustrates this point in a greatly exaggerated form. Let M represent the moon moving round the earth, and let the moon's original velocity be such, that if the earth did not exist, its satellite would travel from O to M or M to A in, say, one second. Now imagine the earth to come into existence when the moon is at M. Then instead of reaching the point A, the moon appears in the position B at the end of a second, having travelled in the direction MB. The distance AB or MC therefore represents the fall of the moon towards the earth in one second. The earth pulls the moon towards itself, the moon has an original, straight-line velocity, and the result of the combination of action is that our satellite strikes a mean, as it were, between the two, and describes a curve. If the original velocity were greater, the orbit described by the moon would be larger than it is, while the reverse would be the case had the tendency to travel in a straight line been less.

Kepler's Laws.—About 1,610 Kepler, from a discussion of the observations of Tycho Brahe, formulated three laws of planetary motion, which can be stated as follows:—

(1) The orbit of each planet is an ellipse, the sun being at one of the foci of each ellipse.

(2) The line joining the centre of a planet to the centre of the sun (the radius vector) sweeps over equal areas in equal times.

(3) The squares of the times of revolution of all the planets are proportional to the cubes of the mean distances from the sun.

These laws apply equally well to the motions of satellites round their primary planets. The first law has already been referred to; but explanations of the meaning of the two remaining laws will now be given.

Kepler's Second Law.—It follows from this law that any body in orbital revolution moves fastest when nearest its primary and slowest when most distant. Let the ellipse of Fig. 47 represent the orbit of a planet or satellite, and let AB, CD, and EF represent the distances traversed by the body in question in a fortnight. The shaded portions of the figure are the areas which the radius vector passes over in each case, and Kepler's second law asserts that these areas are all equal to one another. At the time of discovery, it was not known why this should be the case; but Newton proved that the law of gravitation fully accounted for the motion.

Kepler's Third Law.—This, also known as 'The Harmonic Law,' gives precisely the relation that exists between the motion and distances of bodies revolving round each other. It is expressed in the form of a proportion as follows:—

$$\text{Square of Period A} : \text{Square of Period B} :: \text{Cube of Distance A} : \text{Cube of Distance B}$$

where A and B represent any two planets.

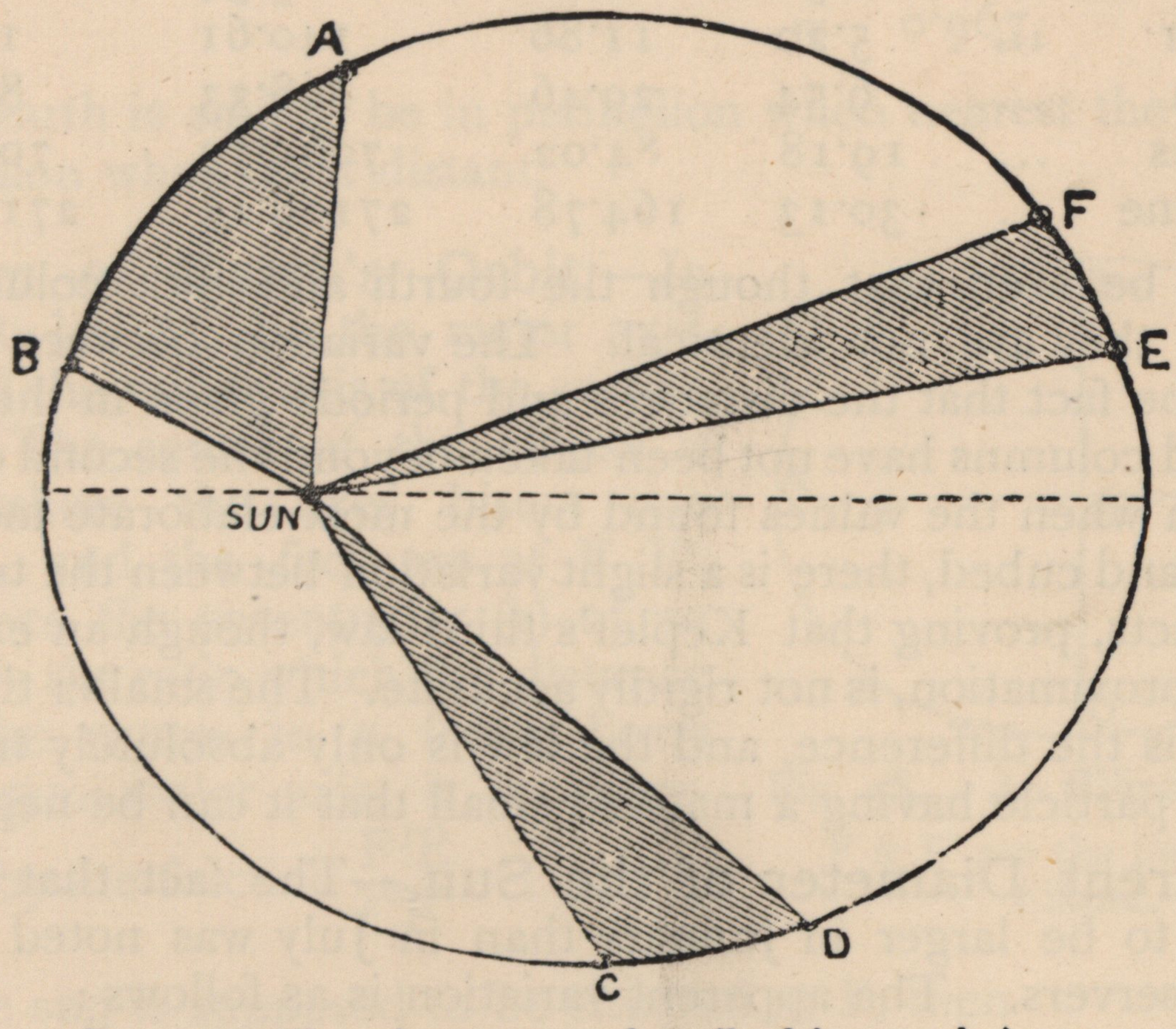


Fig. 47. Equal areas are described in equal times.

Suppose, for example, a planet is found to have a period of ten years; its distance from the sun, in terms of the distance of the earth or any other planet, can be calculated. Let us take the case of the earth for the comparison. Then we have

$$(1 \text{ year})^2 : 10^2 :: 1^3 : \text{Dist.}^3$$

$$\text{Therefore Dist.}^3 = \frac{10^2 \times 1^3}{1^2} = 10^2 = 100$$

And, therefore Distance $= \sqrt[3]{100} = 4{\cdot}6$.

Hence, the hypothetical body is at a distance from the sun 4·6 times the mean distance of the earth, and hence, if the absolute distance of the earth is known, the distance of any other planet can be calculated as soon as its period of revolution has been obtained by observation.

The following table contains the squares of the periods and the cubes of the distances of the chief planets, with the period and distance of the earth as unity :—

Planet	Distance	Period	(Distance)^3	(Period)^2
Mercury ...	0·38	0·24	0·05	0·05
Venus ...	0·72	0·62	0·37	0·38
The Earth ...	1·00	1·00	1·00	1·00
Mars ...	1·52	1·88	3·54	3·54
Jupiter ...	5·20	11·86	140·61	140·70
Saturn ...	9·54	29·46	868·33	867·89
Uranus ...	19·18	84·02	7065·79	7059·36
Neptune ...	30·13	164·78	27108·14	27152·45

It will be seen that though the fourth and fifth columns run together they are not identical. The variation between them is due to the fact that the distances and periods given in the second and third columns have not been taken beyond the second decimal. But even when the values found by the most elaborate means are squared and cubed, there is a slight variation between the two series of products, proving that Kepler's third law, though an extremely close approximation, is not rigidly accurate. The smaller the planet the less is the difference, and the law is only absolutely true for a material particle having a mass so small that it can be neglected.

Apparent Diameter of the Sun.—The fact that the sun appears to be larger in January than in July was noted by very early observers. The apparent variation is as follows :

Sun's apparent diameter in January	...	$32' 36''$
" " " July	...	$31' 32''$
Difference	...	$1' 04''$

The cause of this difference is the earth's varying distance from the sun. We are nearest to the source of our light and heat in January, and at the greatest distance in July. The apparent change of size is not abrupt. There is a gradual decrease from January to July, and a following increase from July to January.

Since distance is connected with the unit of circular measure ($206{,}265''$) in the manner described on p. 81, we get the proportion—

$$\text{Distance of Sun} : \frac{\text{Real diameter}}{\text{of Sun}} :: \frac{\text{Unit of}}{\text{Circular}}\ \frac{:}{\text{Measure}}\ \frac{\text{Apparent}}{\text{Diameter}}\ \frac{:}{\text{of Sun.}}$$

$$\text{That is, Distance of Sun} = \frac{206{,}265'' \times \text{Real diameter}}{\text{Apparent diameter.}}$$

But both the quantities in the numerator of this fraction are constantly the same; the two variable values are the sun's distance and the sun's apparent diameter, and from the equation it will be seen that the former is inversely proportional to the latter. Hence

Least Distance : Greatest Distance :: $31'32''$: $32'36''$

That is, :: $1892''$: $1956''$

= 0·967.

The earth is said to be in perihelion when nearest the sun, and in aphelion when most distant.

Form of Earth's Orbit.—In Fig. 48, let AC be the major axis, and BD the minor axis of the earth's orbit. The centre of the ellipse is at E, where the axes bisect one another, and the foci are at F F′. And since the eccentricity (e) of an ellipse is the ratio which the distance from the centre to a focus bears to the semi-major axis, it is represented by the fraction $\frac{F'E}{CE}$

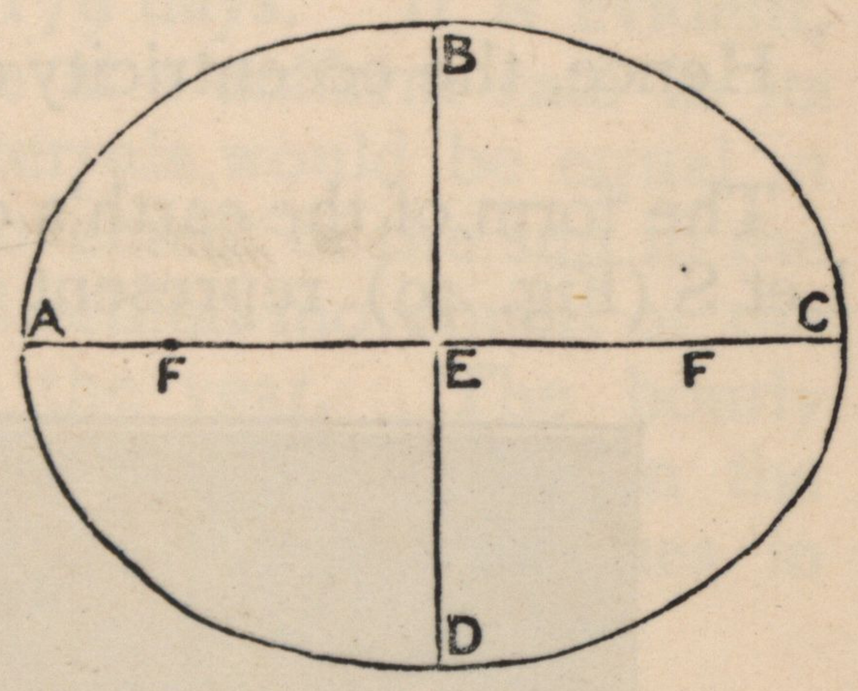


Fig. 48. An Elliptical Orbit.
F & F′ are the foci of the Ellipse.

If the sun is supposed to be situated at F, then

AF = Perihelion Distance,
CF = Aphelion ,,
CE = Mean ,,

Then $CF = CE + EF$

But $EF = CE.\ e$ (for $\frac{FE}{CE} = e$)

Therefore $CF = CE + CE.e$.

Similarly, $AF = AE - FE = CE - F'E$

But $F'E = CE.e$ (for $\frac{F'E}{CE} = e$)

Therefore $AF = CE - CE.e$.

Let Perihelion Distance = P, Aphelion Distance A, and represent the Mean Distance by 1.

Then, from the above equations,

$$A = 1 + e \text{ and } P = 1 - e;$$

But $e\,(A + P) = A - P$,

$$\text{Therefore } e = \frac{A - P}{A + P}$$

And dividing by A, we get $e = \dfrac{1 - \frac{P}{A}}{1 + \frac{P}{A}}$

In the preceding paragraph $\frac{P}{A}$ is shown $= 0{\cdot}967$

Hence, the eccentricity of the earth's orbit $= \dfrac{1 - 0{\cdot}967}{1 + 0{\cdot}967} = 0{\cdot}017$.

The form of the earth's orbit can also be determined graphically. Let S (Fig. 49) represent the sun, and the other letters represent

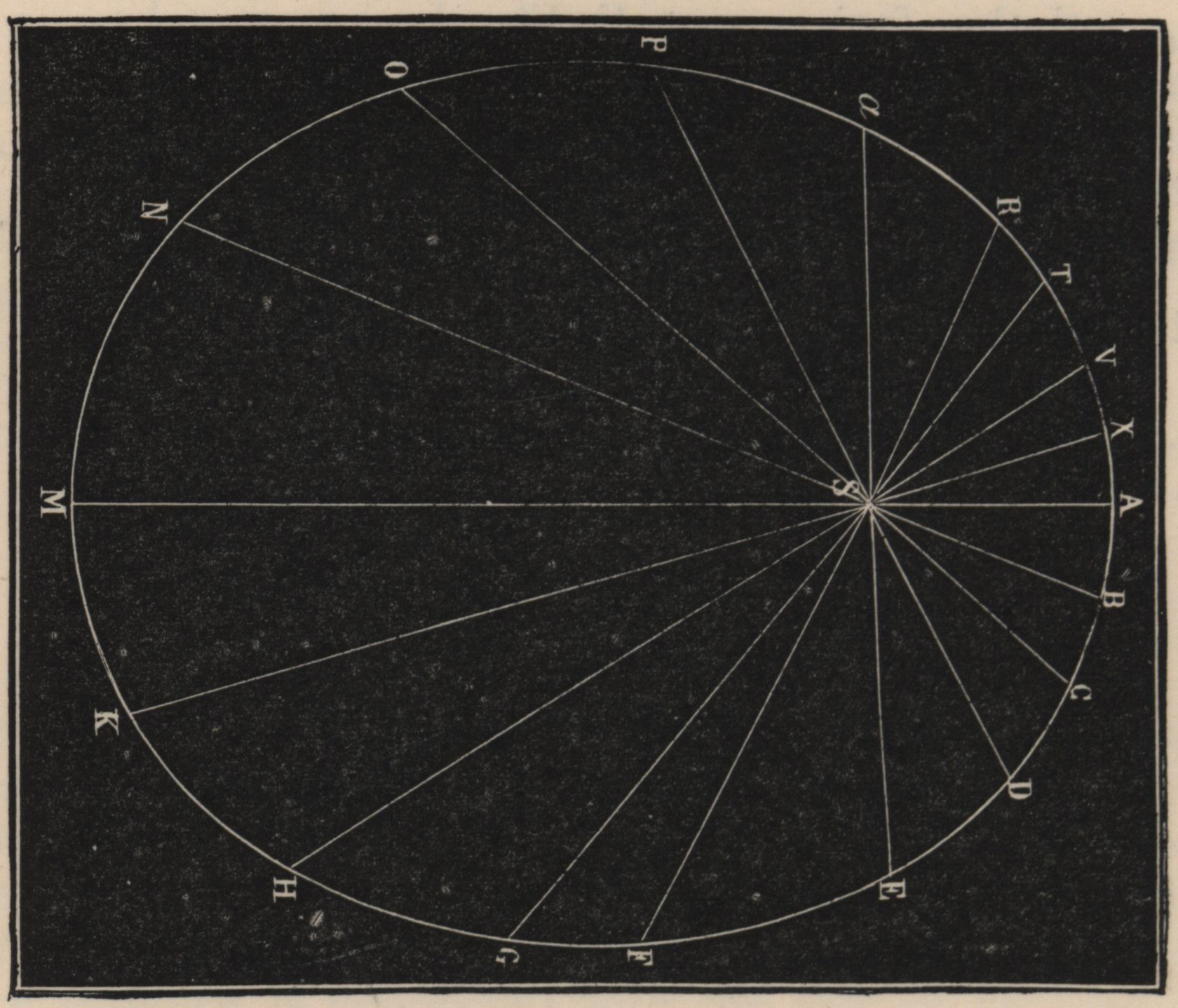


Fig. 49. Method of determining the form of the Earth's Orbit.

positions occupied by the earth at different times of the year. If we take *a* to indicate the position of the first point of Aries, then the angle *a*SP is the earth's longitude after a certain interval of

time; *a*SO the longitude after a longer interval, and so on, up to 360°. Now if we measure the sun's apparent diameter when the earth is at *a* and P and O, and all the other positions shown, and set off distances from S inversely proportional to the values obtained, the figure constructed by joining the ends of the lines is an ellipse. The earth's longitude is the sun's longitude plus 180°, hence by observing the position of the sun in the ecliptic throughout the year and the apparent diameter of our luminary, the exact form of the earth's orbit is found.

The Earth's Motion.—The interval from the vernal equinox to the autumnal equinox is 186 days, while the interval from the autumnal to the vernal equinox is only 179 days. It is evident, therefore, that the earth does not move at a uniform rate in its orbit, for were this the case the two intervals would be equal in length. In fact, the apparent rate of movement of the sun in the sky, which is but a reflection of the real orbital movement of the earth, varies hour by hour throughout the year. The hourly variation of the Sun's Right Ascension (R.A.) is given in the 'Nautical Almanac' and other publications, and its values in December and June are shown below.

December 24, hourly variation of the Sun's R.A., 11·11 secs.
June 20, " " " " 10·40 "

From this it will be seen that the sun appears to move quicker in December than in June; in other words, the earth moves faster in the former than in the latter month. We can sum up the facts stated in this and the preceding section by saying that in winter, when the earth is nearest the sun, it moves faster than in summer, when it is more distant.

The Earth's Volume, Mass, and Density.—When the radius of the earth has been obtained by the methods previously described, the surface and the volume can be calculated. Let r represent the mean radius of the earth (3953·8 miles), and π the ratio of the circumference of a circle to its diameter (3·1416); then we get the following numbers:—

Surface of earth $= 4 \pi r^2 =$ about 197,000,000 square miles.
Volume of earth $= \frac{4}{3} \pi r^3 =$ about 260,000,000,000 cubic miles.

These measures give no idea as to the earth's mass, that is, the quantity of matter it contains; or its density, that is, its weight compared with a sphere of water having the same size. But since mass = density × volume, it can be found when the two values

on the right-hand side of the equation have been estimated. A number of determinations of the earth's density have been made, different observers adopting different methods. The chief methods will now be described.

The Schiehallien Experiment.—The theory of this experiment is as follows:—Let *Za Z'b* (Fig. 50), represent the directions taken by two plumb-lines hung at *a* and *b* respectively, if the mountain shown did not exist. Knowing the inclination of these directions to each other, and the distance *ab*, the position of the point E can be calculated. Now, imagine that a mountain is created and placed upon the plain *ab*. The mountain would attract the plumb-lines out of the vertical, and make them take up the directions *zm*, *zn*. and these lines would meet at C. The deviation from the true direction therefore represents the resultants of the pulls of the mountain and the earth. The size of the mountain can be measured, the average density of the rocks composing it can be found by experiment, hence the mass can be calculated. The problem can then be enunciated as follows:—A mountain of a known mass causes a certain deflection of the plumb-lines; what mass is necessary to counteract entirely the pull of the earth? The mass thus found will be equal to the mass of the earth.

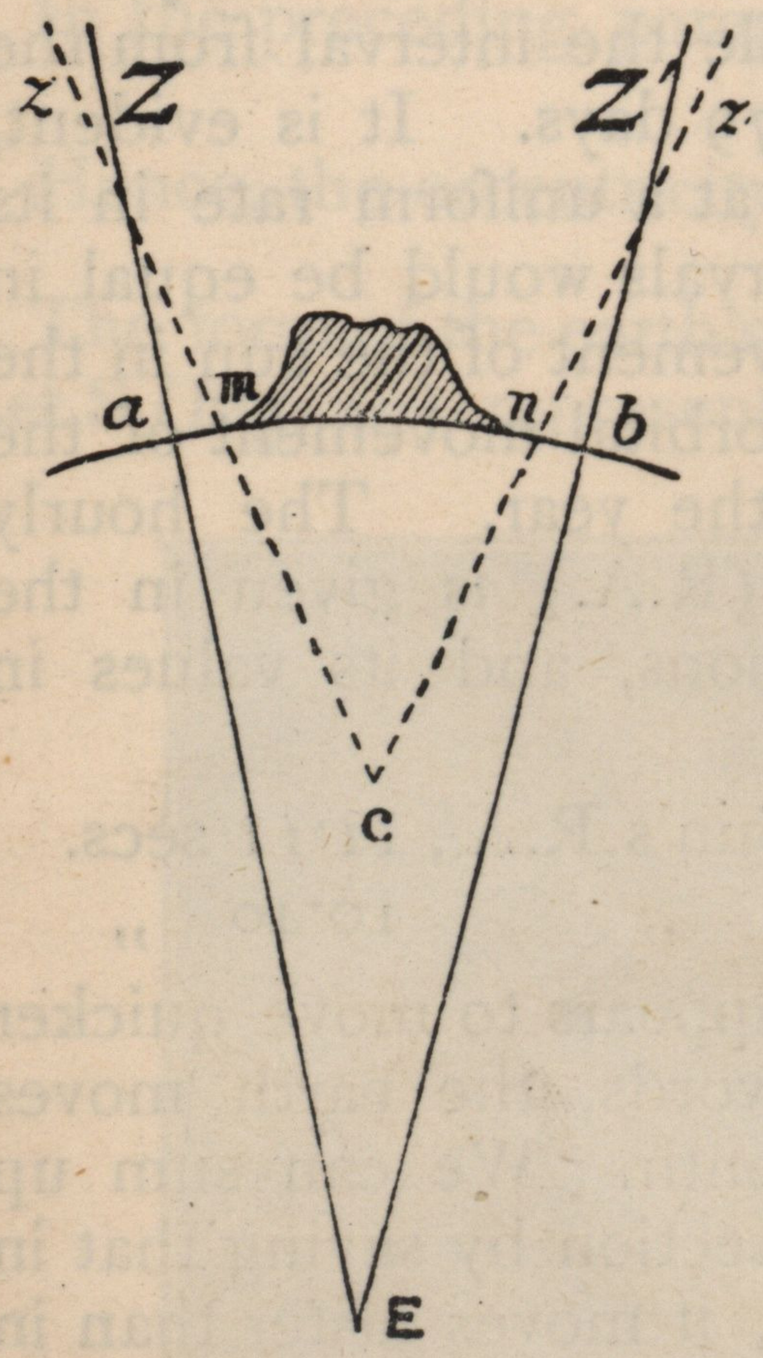


Fig. 50.
Principle of the Schiehallien Experiment.

In 1774 Maskelyne made some observations near the Schiehallien Mountain in Scotland, with a view of obtaining the required data. By means of a zenith sector, the astronomical difference of latitude between two observing stations was found. Calculation showed what the difference would have been had no local attraction existed. The observed difference exceeded the calculated by 11″·6. We thus get:—

Attraction of Earth : Attraction of Mountain :: 206,265″ : 11″·6

That is :: 17781 : 1.

The mountain was then measured, and its volume determined. The ratio of the attraction of the earth to the attraction of a body as big as the earth, made up of the same materials as the mountain, was afterwards estimated, and found to be as 9933 is to 1.

Hence—

$$\frac{\text{Attraction of real Earth}}{\text{Attraction of fictitious Earth}} = \frac{17781}{9933} = 1{\cdot}79.$$

The value 1·79 represents the number of times that the earth's mean density exceeds the density of the mountain. And since the average density of the rocks which make up the mountain was found by experiment to be 2·8,

$$\text{Density of Earth} = 2{\cdot}8 \times 1{\cdot}79.$$
$$= 5{\cdot}012.$$

The Earth's Density from Pendulum Observations.—It has been abundantly proved that the intensity of gravitational stress varies inversely as the square of the distance from the earth's centre. The intensity at any point above the earth's surface can therefore be calculated. A pendulum is kept in vibration by the attraction of the earth, and, applying the law of gravitation, the slowing down which would follow if it were removed to any point higher in the atmosphere can be found. But the value obtained would only be true if the pendulum could be set in vibration in the air, away from all local influences. This state of things is of course impracticable. We can, however, find the rate of vibration at the bottom and at the top of a mountain. The rate at the top will be quicker than it would have been had the mountain not existed. And the difference between the observed and theoretical values is produced by attraction of the mountain. If, therefore, the mass of the mountain is found by measurement and experiment, and the effect of the mass upon a pendulum rate is determined by observation, the action of a similar mass of the same size as the earth can be estimated by proportion. The earth's density is then deducted from this as in the case of the Schiehallien experiment.

Pendulum Experiments in Mines.—Another method is to find the rate of a pendulum at the earth's surface and in a mine. It has been proved geometrically that 'if the different points of a spherical surface attract equally, with forces varying inversely as the squares of the distances, a particle placed within the surface is not attracted in any direction.' Hence, if a pendulum is taken down a mine and set in vibration, the result obtained is the same as it

would have been if the whole shell of matter above it had been entirely removed. The removal of this shell means a diminution of the earth's mass, taken as a whole, and therefore a diminution of the force of gravity, and of the rate of the pendulum. But the attractions of spheres of uniform density for points on their surfaces are proportional to their radii. On this account the attraction of the pendulum is increased as the earth's centre is approached, and the pendulum-rate must therefore be increased. As a matter of fact, if the earth had the same density throughout, like a billiard ball, a seconds pendulum at the surface would lose when taken down a mine, the loss being brought about by taking out of action, as it were, the exterior shell of rock. Observations show that such a pendulum beats quicker; hence the earth increases in density as its centre is approached. The density of the part of the shell near the mine can be found as in the Schiehallien experiment, and the effect of its mass in tending to slow down the pendulum can be calculated. This mass and its effect is then compared with the mass of the sphere below the bottom of the mine and its own effect, and from the proportional results the average density and the mass of the earth can be found.

The Earth's Density determined by means of a Balance.—Dr. Poynting has obtained some good results by very simple means. A delicate balance has a spherical mass of lead and antimony suspended from each of its arms. A much larger mass of the same alloy is then brought in turn beneath the balanced spheres. When the attracting mass is on one side, the sphere above it is pulled slightly down; when on the other side, the companion sphere is pulled down. The attraction stress between the mass and each sphere is thus measured. The weights of the spheres give the value of the earth's attraction upon them, and the density of the earth can then be calculated in the same manner as that described in the next paragraph.

The Cavendish Experiment.—At the end of the last century Cavendish determined the earth's density by what is known as the 'torsion-balance' method. Two small lead balls of known weights are rigidly connected by a rod. The rod is suspended by a fine thread attached to its centre, and comes to rest in a certain position. Two massive lead balls are now brought alongside the small balls in such a manner that their attraction tends to twist the fine thread. The small balls are pulled out of their original direction, and the amount of deviation is measured. From this

the effect which would be produced if the large balls were of the same size as the earth is calculated. The weight of each of the small balls is a measure of the earth's attraction. Hence we get the proportion :—

Attraction of a lead ball of the same size as the earth	:	Attraction of the earth	::	Density of lead	:	Density of the earth.

And substituting the results of observation, 2 : 1 :: 11·4 : density of earth.

Whence density of earth = 5·7.

The experiment can also be viewed from the following aspect :—

The earth's diameter is about 40,000,000 feet, and since the volumes of cubes vary according to the cubes of their diameters, the attraction of a sphere one foot in diameter of the same mean destiny as the earth is $\frac{1}{(40,000,000)^3}$ of the earth's attraction. A sphere of lead one foot in diameter exerts about twice this attraction; hence the density of the earth is about half that of lead.

Cavendish's experiment in a modified form has been carried out by several eminent investigators. Professor Cornu suspends the rod, on which are fixed the two small balls between four hollow globes, situated at the corners of an oblong. The globes at the extremities of one of the diagonals are first filled with mercury and the deflection of the suspended beam observed. They are then emptied, the two remaining globes are filled, and the deflection in the opposite direction is measured. The advantages of this ingenious method over that of Cavendish are obvious. Professor Boys has also devised an entirely new arrangement, in which one of his famous quartz fibres is utilized, and the disturbing masses are two gram weights. The results obtained with this apparatus have not yet been published.

Mass and Weight of the Earth.—The mean value for the density of the earth, arrived at by numerous investigators, is 5·6; that is to say, the earth is 5·6 times heavier than if it were composed of water. Now the volume of the earth has been stated to be about 260,000,000,000 cubic miles; and the weight of a cubic mile of water is about 4.100,000,000

tons. Hence, if the earth had the same density as water, its weight would be

260,000,000,000 × 4,100,000,000 tons,

That is, 1,066,000,000,000,000,000,000 tons.

But the earth's density is 5·6 ; its weight is therefore

1,066,000,000,000,000,000,000 × 5·6 tons

= 5,969,600,000,000,000,000,000 tons,

Or. roughly speaking,

6,000,000,000,000,000,000,000 tons.

In astronomical problems, however, the earth's mass in tons is not required, but only its mass relatively to other bodies.

The Centre of Mass.—If a very heavy weight (B) is fixed at one end of a rod, and a lighter weight (A) at the other, it is known that the balancing point would be much nearer the former than the latter. (Fig. 51.) This point is called the *centre of gravity*, but is more correctly termed the centre of mass or inertia. Its distance from A or B is inversely as the masses of these bodies. Thus, if B has six times the mass of A, the distance of A from the centre of mass is six times greater than the distance of B from the same point. Although no rod joins the earth to

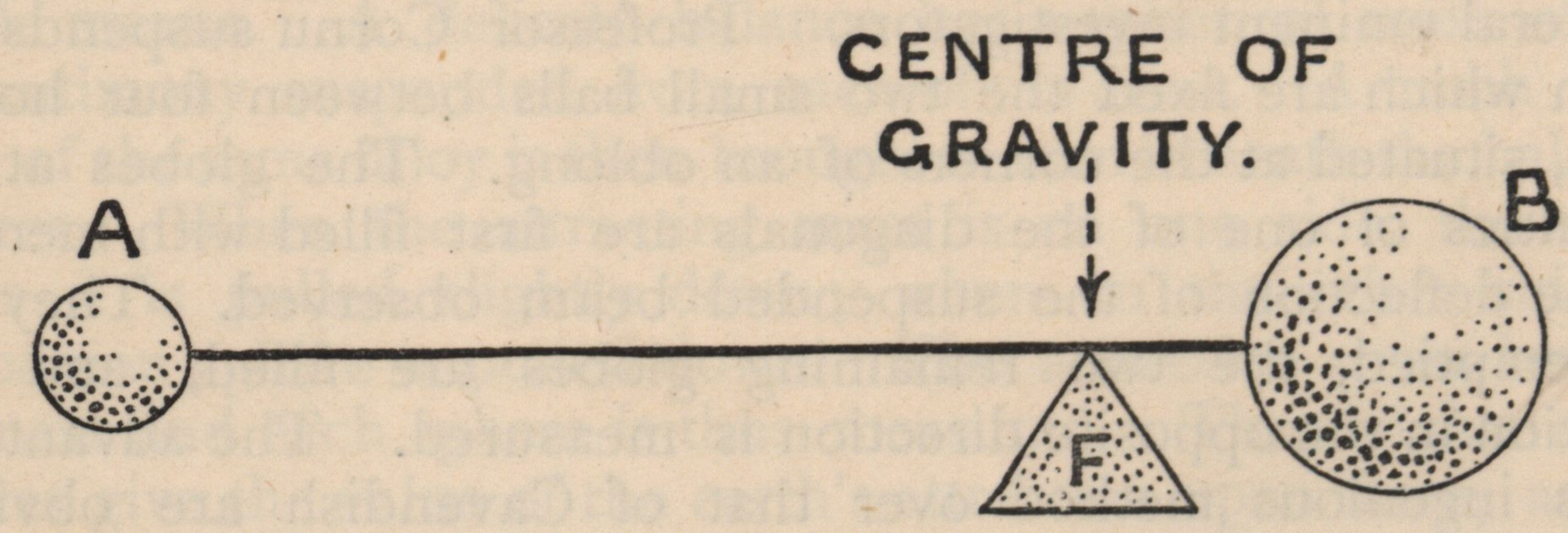


Fig. 51. The Centre of Gravity of two connected Masses.

the sun the same law prevails, and since the sun is 332,000 times heavier than the earth, the centre of mass of the two bodies is 332,000 times nearer to the sun's centre than it is to the centre of the earth. Now it can be shown that revolving bodies go round their common centre of mass, hence the earth revolves round the centre of mass of itself and the sun and not around the sun; but the sun's mass is so much greater than the earth's mass that their common centre of mass is inside the former, hence it is usual to speak of the earth as revolving round the sun. Similar

reasoning applies, of course, to the motion of the other planets round the sun, and also of the satellites round their respective planets. It is interesting to note that if all the members of our system, except the sun, were put in one pan of a balance they would only weigh about $\frac{1}{750}$ as much as our luminary.

We have said that

Mass of A : mass of B : : BF : AF.

Hence if the mass of A is known, and either the distance AF or BF can be measured, the mass of B can be calculated, and the masses of A and B can be at once compared when their distances from the centre of mass have been found, the comparative values not necessitating a knowledge of the absolute mass of either body.

Mass, Force, and Acceleration.—The law of gravitation is stated by Clerk Maxwell as follows :—

'Every portion of matter attracts every other portion of matter, and the stress between them is proportional to the product of their masses divided by the square of their distance.' Let f represent the gravitational stress, m and m^1 any two portions of matter in the universe, and d the distance between them; then the law of gravitation is expressed algebraically in this manner :—

$$f = \frac{m \times m^1}{d^2}$$

The force of gravitation, or gravitational stress, like other forces, is measured by the product of mass (m) into the acceleration (a) produced, that is,

$$f = ma.$$

The acceleration produced thus varies directly as the intensity of the force in action. If two equal forces act upon unequal masses, the acceleration produced in the larger will be less than that produced in the smaller, but in each case the mass multiplied by the acceleration will give the same result. Or, if equal masses are found to have unequal accelerations, the one with the larger acceleration must be acted on by a greater force than the other. This being so, to compare the masses of two bodies it is only necessary to apply to each of them the same force and compare the accelerations produced.

Mass of the Moon.—Let S, E, and M (Fig. 52), represent the positions of the sun, earth, and moon, at a given moment, and G the centre of gravity of the earth and moon. The sun

attracts the earth and moon in the directions MS and ES, and it can be shown that the effect is the same as if the sum of the masses of the two bodies were situated at G. This is the point which really travels round the sun in an ellipse. ME is about $\frac{1}{400}$ of SE. While G is describing the ellipse, the line ME is in constant revolution and coincides with GS at new and full moon. If, therefore, we could observe the angular movement of the earth from the sun, it would be found to be represented by the movement of the line SG augmented or diminished by the small angle GSE as the earth was swung forward or backward by the moon's motion, and would be greatest at the first and last quarter. But the revolution of the earth is reflected by the motion of the sun in the ecliptic. Every $14\frac{1}{2}$ days the sun should have its motion quickened or retarded, and investigation shows that this monthly inequality really exists and is at a maximum when the moon is in quadrature. The angle by which the sun is in advance or behind its normal position at these times is $6''.5$. This then is the angle GSE in the figure. Knowing that SE is 400 times greater than MF, and that in the triangle ESG (supposed to be right-angled at E) the angle ESG is $6''.5$, a simple calculation permits the determination of the ratio which MG bears to EG. The value found is as 81 : 1. And since the distance of G from M and E is inversely proportional to the masses at these points, it is concluded that the mass of the moon is $\frac{1}{81}$ that of the earth.

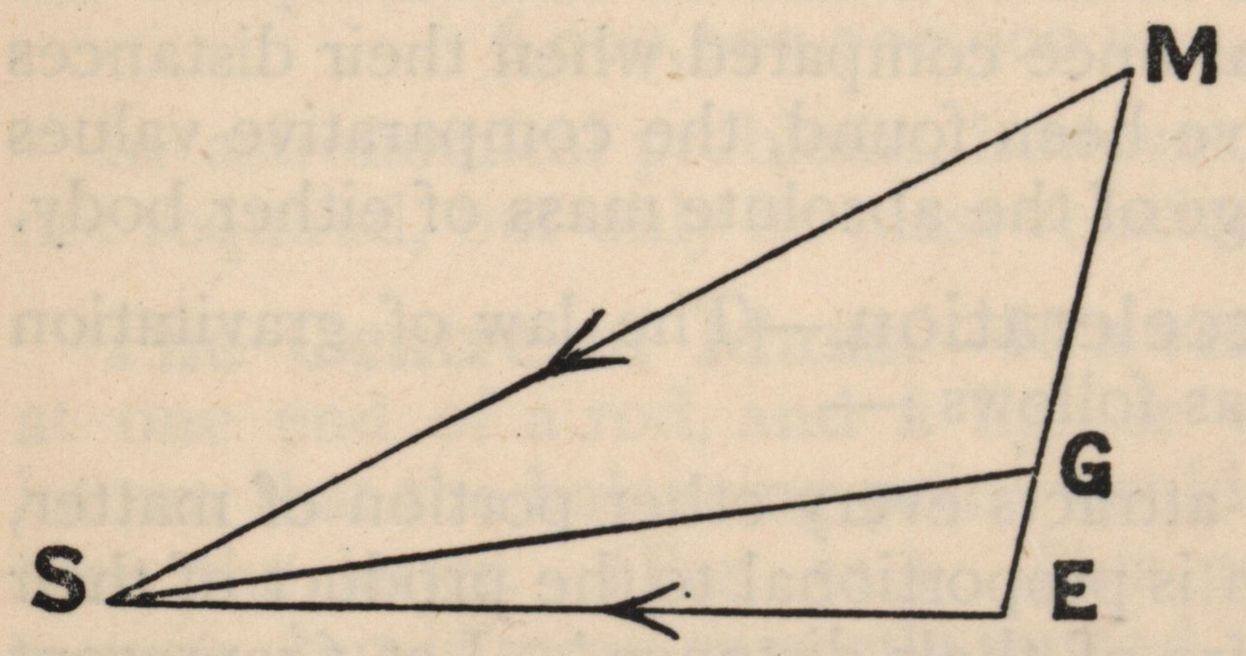


Fig. 52. Method of determining the Mass of the Moon.

Mass of the Sun.—If a body is placed in succession at the same distance from the sun and the earth, it will be attracted towards each with a force which is proportional to their masses. And since the space traversed by a body is directly proportional to the acceleration, if during the first second the body fell one inch towards the earth and 330,000 inches towards the sun, it would be obvious that the sun had a mass 330,000 times greater than the earth. In a similar manner, by applying the law of inverse squares, the relative masses of the sun and earth can be found when the distance of the body from each is not the same. We

find that the earth falls towards the sun 35 feet in one minute, and that our moon falls towards the earth 16 feet in the same time. But the earth is 386 times nearer the moon than it is to the sun, so correcting for difference of distance we get :—

$$\text{Moon's fall at sun's distance} = \frac{16}{386^2} \text{ feet per minute}$$
$$= 0{\cdot}000108 \text{ feet per minute.}$$

We see, therefore, that the sun's force of attraction produces an acceleration of 35 ft. per minute on the earth ; the earth would produce an acceleration of 0·000108 ft. per minute on the moon if it were as far away as the sun. Hence,

Sun's mass : earth's mass :: 35 : 0·000108.

That is, as 323,000 is to 1.

The accuracy of the determination depends upon our knowledge of the distances of the sun and moon.

Masses of Planets having Satellites.—The mass of a planet having one or more satellites can be found by the same method as that employed in the case of the sun, viz., by comparing the fall of the satellite towards the planet with the fall of the planet towards the sun, both falling bodies being considered at the same distance. Kepler's third law is used for expressing the mass m of a planet in terms of the sun's mass, the formula being :—

$$\frac{m}{M} = \left(\frac{a'}{a}\right)3 \left(\frac{T'}{T}\right)2$$

where a is the semi-major axis of the planet's orbit, and T the time of revolution round the sun ; a' and T′ representing similar terms for the satellite.

In the case of Jupiter, observations of the four satellites may be made, and the mean result taken. A recent determination by M. Schur gave the value $\frac{1}{1047\,232}$ as compared with the sun.

Saturn's mass has been obtained from observations of its two largest satellites, Titan and Japetus. Bessel's researches made it $\frac{1}{3502}$, while Struve found a value $\frac{1}{3498}$. This roughly gives the fraction $\frac{1}{3500}$ as the planet's mass.

Before the discovery of the Martian satellites by Hall, the mass of the planet was a matter of great uncertainty. The discoverer's observations of the satellites led him to assign $\frac{1}{3100000}$ as the mass of Mars, a result probably not far from the truth.

Masses of Planets without Satellites.—For the determination of the masses of Venus and Mercury, a different and much less exact method of procedure is used. If the masses of Venus and the earth were known, the perturbations they would give to the motion of Mercury could be easily calculated. Let the orbit be found which Mercury would have if it existed alone with the sun, and then let its true path be determined. By comparing the two results, the disturbing effects of Venus and the earth can be estimated. In a similar manner, the calculated and true paths of Venus can be compared, the disturbing masses being Mercury and the earth. In this way a series of equations is obtained from which the masses of Mercury and Venus may be isolated.

Mass of Jupiter.—The enormous mass of Jupiter shows itself in its effects upon many bodies in our system, especially upon the motions of comets. The comet of Lexell may be taken as a typical case. In 1769 this comet approached very near to Jupiter, and by the planet's action was brought within our range of vision and given a period of $5\frac{2}{3}$ years. Its return in 1776 could not be observed, and before another revolution could be completed, viz., in 1779, the comet was shown by Lexell to have again approached very near to Jupiter, nearer than the fourth satellite. The probable result was that the elliptic orbit was transformed into a parabolic one by the predominance of the planet's attraction over that of the sun, and the comet left our system for a time. In 1889, however, a comet was observed which is very probably the one that had been lost. From observations of the perturbations of Winnecke's comet, Haertl found Jupiter's mass to be $\frac{1}{1047.175}$ that of the sun, while Faye's comet gave the value $\frac{1}{1047.788}$.

Some of the asteroids approach very near to Jupiter, and from observations of the motion of one of them the planet's mass has been found $\frac{1}{1047.538}$. Estimations have also been made by observations of the perturbations of Saturn, but, since the necessary series should cover a cycle of 900 years, and only 120 years are available, the method is not yet very exact. This accounts for the anomalous result, $\frac{1}{1070.5}$, found by Bouvard in 1821.

Planets compared with the Earth.—The following are the masses of the planets given by M. Tisserand, with the earth as unity :—

Mercury	$\frac{1}{16}$.	Jupiter	310.
Venus	$\frac{4}{5}$.	Saturn	93.
The Earth	1.	Uranus	14.
Mars	$\frac{1}{10}$.	Neptune	17.

The methods of determining the mean density and mass of the earth have been explained, and knowing the relative masses of the planets, as given in the above table, we can express their weights in pounds.

Masses of Asteroids.—The perturbing effect of each asteroid is to give a motion to the line of apsides of Mars' orbit. The sum of these effects is the same as would be produced by taking a mean orbit of all the asteroids and distributing them uniformly in it. Leverrier made a calculation on the assumption that the total mass of the asteroids was equal to that of the earth, and he found that, if they had a mass only equal to one-fourth that of the earth, Mars would be disturbed by an amount clearly perceptible to us. Swedstrup has found the assumption too high, and has calculated that the sum of all the asteroids known up to August, 1880, is only about $\frac{1}{4000}$ of the earth's mass, or about $\frac{1}{50}$ that of the moon. Three comparatively large asteroids have had their diameters measured. Sir W. Herschel found the apparent diameters of Ceres and Pallas to be $0''\cdot35$ and $0''\cdot24$ respectively. The corresponding real diameters are 155 and 106 miles. For Vesta, Madler found an apparent diameter of $0''\cdot65$, or 290 miles. If these bodies are supposed to have the same density as the earth, their proportional masses are as follows :—

Ceres	$\frac{1}{130000}$.
Pallas	$\frac{1}{420000}$.
Vesta	$\frac{1}{20000}$.

Masses of Jupiter's Satellites.—These bodies, so proportionally small, the greatest being only $\frac{1}{10000}$ of the planet's mass, cannot have their measures accurately determined by measurement of the angle subtended by the line joining the centre of the planet to the common centre of gravity. The best method of determining the masses of the satellites in this case is to measure their disturbances upon each other. The method was propounded

and worked out by Laplace with the following results in terms of Jupiter's mass :—

First Satellite	$\frac{1}{59000}$.	Third Satellite	$\frac{1}{11000}$.
Second ,,	$\frac{1}{43000}$.	Fourth ,,	$\frac{1}{23000}$.

This proportion gives the third satellite a mass about double that of our moon.

Masses of Saturn's Satellites.—Titan, as its name suggests, is the largest of the family, and consequently exercises a considerable influence over the others. Professor Hall has found that under its action the major axis of Hyperion's orbit makes a complete revolution in about 18 years. Other astronomers have investigated the matter, Professor Pickering comparing the diameters of the other satellites with that of Hyperion by photometric means, and, if they all have the same density, the following numbers represent their masses, Saturn's mass being unity :—

Mimas	$\frac{1}{500000}$.	Rhea	$\frac{1}{32000}$.
Enceladus	$\frac{1}{270000}$.	Titan	$\frac{1}{4700}$.
Tethys	$\frac{1}{75000}$.	Hyperion	$\frac{1}{1800000}$.
Dione	$\frac{1}{85000}$.	Japetus	$\frac{1}{110000}$.

The mass of Saturn's rings has been found $\frac{1}{620}$ that of the planet by observations of the rotational movement which it imparts to the major axis of the orbits of the satellites.

Masses of some Stars.—Sir William Herschell was the discoverer of the relative motions of double stars in 1802. The obvious conclusion from such a discovery was that the law of gravitation was universal. Truly, it is not logical to make such an assumption, and some objections have been raised, but the *onus probandi* rests with those who doubt it. In considering the motions of the components of a binary star system, it must be remembered that they revolve round a common centre of gravity. It is usual, however, to consider the principal star as fixed and augmented by the mass of its satellite, the latter having an orbit which is the mean of the two. Knowing the fall of the satellite to its primary in one second, we can calculate what it would be if at the same distance from it that the earth is from the sun. But we know by how much the satellite would fall towards the sun, since it would have precisely the same fall as the earth. Hence the consideration of the two falls will give the sum of the masses of the stars in terms of the sun's mass. Let m and m' be

the masses of the two components of a double star; M, that of the sun; a the angle, expressed in seconds, which is subtended at the earth by the semi-major axis of the satellite's orbit; p the 'annual parallax' of the binary group; T the time in years of one revolution of the satellite, then the following formula holds good:—

$$\frac{m+m'}{M} = \left(\frac{a}{p}\right)^3 : T^2$$

The values obtained for four stars are shown below:—

Star.	Parallax.	Magnitude.	Sum of Masses.
α Centauri	0″·80	1	1·3
η Cassiopeiæ	0″·15	4	8·3
70ρ Ophiuchi	0″·17	4·5	2·5
o^2 Eridani	0″·22	4·5	1·0

The Mass of Sirius.—A curious point comes out in connection with Sirius, the brightest star in the heavens. Bessel determined the proper motions of thirty-six stars by comparing their right ascensions in his day with those given by Bradley, but he found that, in the case of Sirius, the hypothesis of a uniform variation was irreconcilable with the observations, and suggested that the irregularities might be produced by the action of some obscure body. After Bessel's death, Peters found that it was possible to account for the irregularities by the supposition that Sirius described an orbit in fifty years, whose eccentricity was about 0·8. Safford, in 1861, from a discussion of the declinations of Sirius, came to the same conclusion as Peters; while Auwers, a year later, after investigating about 7,000 right ascensions and 4,000 declinations, found the time of revolution to be forty-nine years, and the eccentricity 0·601. At the same time as Auwers was engaged with his calculations, Alvan Clark discovered a small star at a distance of about 10″ from Sirius, which appeared to be the companion. Further observation supported the surmise and proved that the body was precisely what was required to account for the orbit of Sirius round the common centre of gravity of its companion and itself. If the parallax of Sirius be taken as 0″·38, the sum of the masses of the two stars is 4·4 times the sun's mass. Sirius has about twice the mass of its companion, and they are separated by a distance a little more than twice the distance of Uranus from the sun.

QUESTIONS ON CHAPTER V.

1. State the methods used in determining the density of the earth. (May, 1892.)

2 State Kepler's laws. (May, 1886.)

3. State what you know about Kepler's laws. (May, 1881.)

4. How has the mass of Jupiter been determined? (May, 1888.)

5. How has the density of the earth been determined? (December 1883.)

6. Prove, by means of Kepler's second law, that the power which keeps the planets in their orbits is directed towards the sun.

7. How is the mass of the sun determined?

8. What is the period of a planet whose mean distance from the sun is three times the earth's mean distance?

9. Give a brief sketch of the means by which the masses of some stars can be found.

10. State any peculiarities of the motion of Sirius with which you are acquainted.

11. Why is it more difficult to determine the mass of Venus or Mercury than that of Mars?

12. How can the eccentricity of the earth's orbit be found?

CHAPTER VI.

THE MOON'S MOTIONS AND CONSEQUENT PHENOMENA.

THE moon is a small body which moves round the earth in an orbit very similar to that in which the earth travels round the sun. It and other satellites are sometimes termed secondary bodies, while the planets themselves are primary bodies.

Elements of the Moon's Orbit.

Mean Distance	238,840 miles
Inclination to the Ecliptic ...	5° 8′ 40″
Eccentricity	$\frac{1}{20}$
Sidereal Period	27d. 7h. 43m. 11·5s.
Synodic Period	29d. 12h. 44m. 2·7s.

Moon's Distance.—It can be proved in a similar manner to that previously described that the moon obeys Kepler's laws of motion, and that her path is an ellipse of which the earth occupies one of the foci. Hence, the distance of our satellite varies; when it is nearest the earth it is said to be in *perigee*, and when furthest away to be in *apogee*. The moon's apparent diameter varies from $29' 22''$ to $33' 32''$. From this difference the eccentricity of the orbit has been found to be $\frac{1}{20}$, that is to say, if the distance from the centre of the ellipse to an extremity of the major axis is represented by 20 inches, the earth's position would be one inch out of the centre. In consequence of this large eccentricity (the eccentricity of the earth's orbit is only $\frac{1}{60}$) the distance of the moon from the earth varies considerably. It may get as near as 221,000 miles or so far away as 259,600 miles; the average distance, however, is about 240,000 miles. The average distance of the sun from the earth is 93,000,000 miles, therefore the moon is only about $\frac{1}{400}$ the distance of the sun from the earth.

Inclination of Orbit.—The orbit of the moon around the earth does not lie in the plane of the ecliptic but is inclined to it at an angle which varies between $5°\ 0'$ and $5°\ 17'$, hence the apparent path described by the moon among the stars is not the same as that described by the sun, viz., the ecliptic, but is inclined to it at an angle of about $5°$. In consequence of this, the moon sometimes describes larger arcs than at other times.

The points where the orbit intersects the ecliptic plane are termed nodes, and the line which is the common section of the two planes is the line of nodes. The ascending node is the point at which the moon appears when passing from south to north of the ecliptic, and the descending node marks the point where the moon just sinks below this plane. The line of nodes has a backward motion along the ecliptic very similar to the motion of the equinoctial line of the earth's orbit, but much more rapid.

Sidereal and Synodic Periods.—The sidereal revolution of the moon is the time occupied in passing from a star to the same star again as seen from the earth, viz., about $27\frac{1}{3}$ days. The synodic revolution of the moon is the length of the lunar month, or the time taken by the moon to pass from full moon to full moon, new moon to new moon, or from any phase to the same phase again, that is, about $29\frac{1}{2}$ days. The relation between the

two periods is the same as that used for the planets. If L represent an ordinary lunar or synodic month, S the sidereal month, and E the length of the sidereal year, we have:—

$$\frac{1}{S} - \frac{1}{E} = \frac{1}{L}$$

Revolution of the Line of Nodes.—The line of nodes of the moon's orbit, that is, the line produced by the intersection of the plane of the orbit with the ecliptic plane, has a rapid retrograde motion along the ecliptic. The effect of this becomes apparent after two or three revolutions. If we observe the moon eclipse a star when she is at the ascending node, the following month she will appear to the north of the star, and the distance will go on increasing from month to month until the angular separation is about 5°. This will be reached about five years after the first observation. In about four years more the moon will have sunk towards the star and eclipses it again. A similar separation south of the star now occurs, reaches a maximum of about 5°, and in about $18\frac{1}{2}$ years from the first observation the moon returns to her original position. In this period the line of nodes moves completely round the sky. The rate of motion amounts to 19° 20′ in a year, or 3′ 10″·6 in a day. This retrograde motion is caused by the varying attraction of the sun upon the moon.

Motion of the Apse-Line of the Moon's Orbit.—The direction of the apse-line can be determined by observations of the moon's apparent diameter, for at the extremities of the line the greatest and least values are reached. In general, the points at which the moon's diameter appears the same are found and the position of the apse-line is taken as midway between them. It is found that this line has a direct motion of about 40° 39′ in a year, that is, 6′ 41″ in a day. Hence a sidereal revolution takes place in 3232·57 days, or rather less than nine years. The movement is, however, subject to considerable fluctuation. There are a number of other periodic inequalities affecting the moon's longitude, and they all have to be taken into account in calculations referring to lunar positions in the past or future. Besides these periodic inequalities, others of a different kind, extending over a number of years and therefore known as *secular* inequalities have been found. The most important of these is the acceleration of the moon's mean motion, of which more is said later on in this book.

The Moon's Apparent Motion.—The movement of the moon among the stars must have been noticed by everyone. To pass from a star to the same star again, that is, to describe a complete circle, the moon takes about $27\frac{1}{3}$ days. The daily motion of our satellite is therefore 360° divided by $27\frac{1}{3}$, that is 13° 11′, or about its own diameter per hour. This is the average rate, the true rate increases from apogee to perigee, and then decreases as the moon's distance is increased.

Lunar and Sidereal Months.—It has been noted that a synodic revolution of the moon is about two days longer than a sidereal revolution, that is, a revolution of the moon with respect to the sun is two days longer than one with respect to the stars. The explanation of this difference is found in the following. The movement of the earth in its orbit from west to east causes the sun to appear to travel eastward right round the heavens in a year. Consider then the sun, moon, and some star on the meridian; in $27\frac{1}{3}$ days the moon will appear exactly in front of the same star,

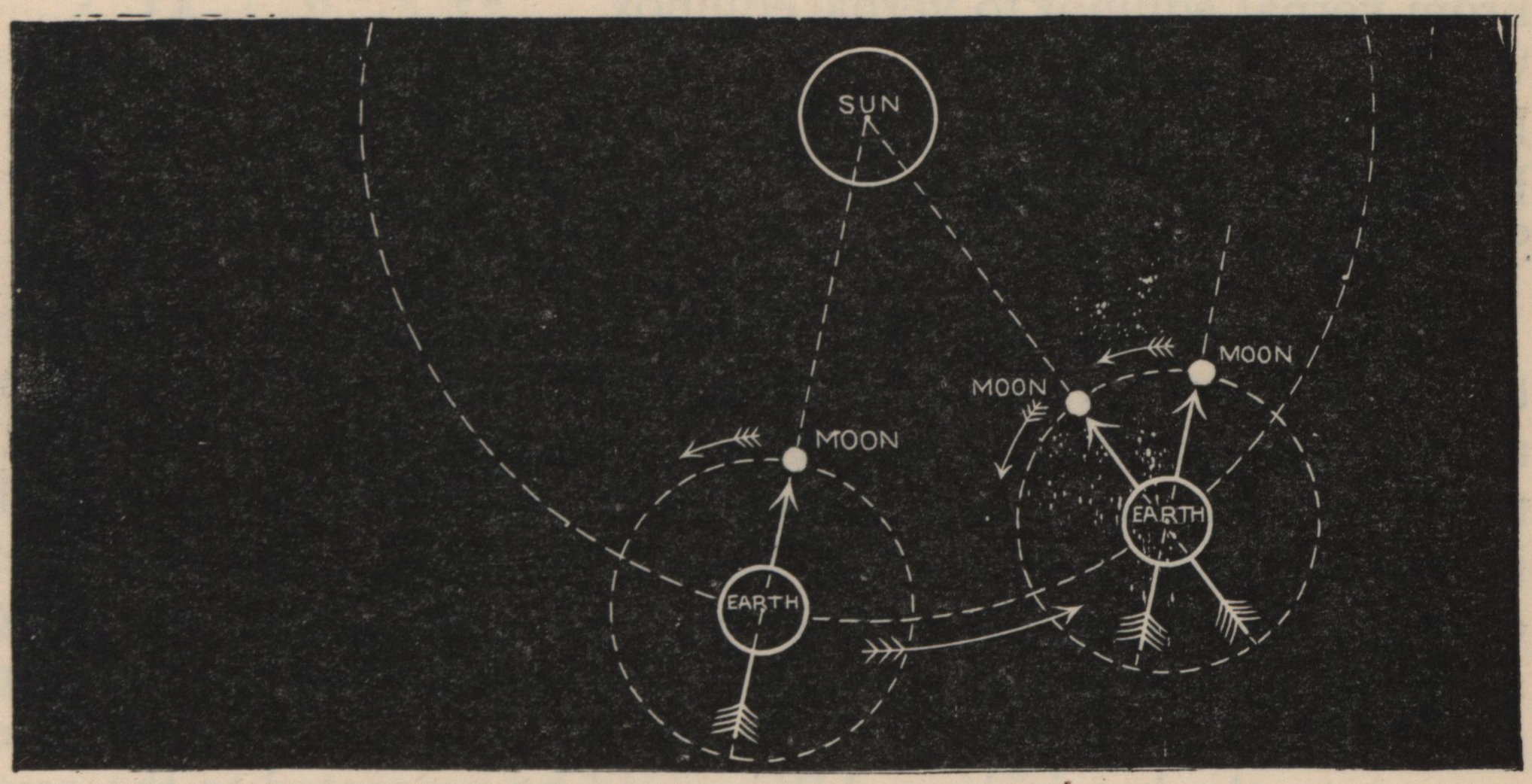


Fig. 53. Cause of the different lengths of the Lunar and Sidereal Months.

but the sun has moved on a little among the stars during that time, and it takes the moon two days to catch up to him again; the two bodies are then on the same meridian as some other star and the cycle begins afresh. Fig. 53 illustrates this point. Let the earth, moon, sun, and a star be in a straight line as indicated by the left hand arrow. When the moon comes again in front of the same star, the earth will have moved on in its orbit and it is not until two days later that the moon comes in front of the sun again.

The Calendar Month.—This is the month employed in civil life and used in the almanacs. Since the moon revolves round the earth in $27\frac{1}{3}$ days she makes a little more than 13 revolutions in a year of 365 days. On account of the revolution of the earth, however, in this time there are only $12\frac{1}{2}$ lunar months of $29\frac{1}{2}$ days. At one time twelve lunar months, that is, 354 days, were taken to make up a year, and since this was 11 days short, an extra month was added to alternate years. Now, however, calendar months are employed, that is, months containing a whole number of days, as 28, 30, or 31, and twelve of these months make up our year. The lunar year of 354 days is still in use among the Moslems.

Different Lunar Periods.—On account of the movements of the points of reference used to determine the rate of the moon's motion, the lengths of different lunar periods are different. The following table exhibits these periods :—

From star to star again	27d.	7h.	43m.	11s.
From vernal equinox to vernal equinox	27	7	43	4
With respect to the sun	29	12	44	3
From perigee to perigee	27	13	18	37
From node to the same node	27	5	5	35
Sidereal revolution of nodes	6,793	6	59	15

Only one side of the Moon is seen.—A circumstance that must have struck the most casual observer is that the moon always presents the same face to the earth. The explanation of this fact is that the moon rotates on its axis in the same time that it takes to perform a revolution round the earth. Let us conceive ourselves to be looking down upon the earth and moon from somewhere in space (Fig. 54). The moon presents the hemisphere BAD to the earth ; let it move through 90°, then, if it did not rotate, the hemisphere ABC would be presented to the earth ; but we know from observation that the same part of the lunar surface is seen—hence, while the moon moves 90° in her orbit she rotates 90° on her axis, and therefore while she completes a revolution around the earth, that is, describes 360°, she also completes a rotation on her axis. The period of revolution with respect to a star—that is, the time that elapses between two successive appearances of the same star over some particular point in the moon—is 27 days 7 hours 43 mins. 11 secs., and this is, therefore, also the time taken by the moon to perform one axial rotation.

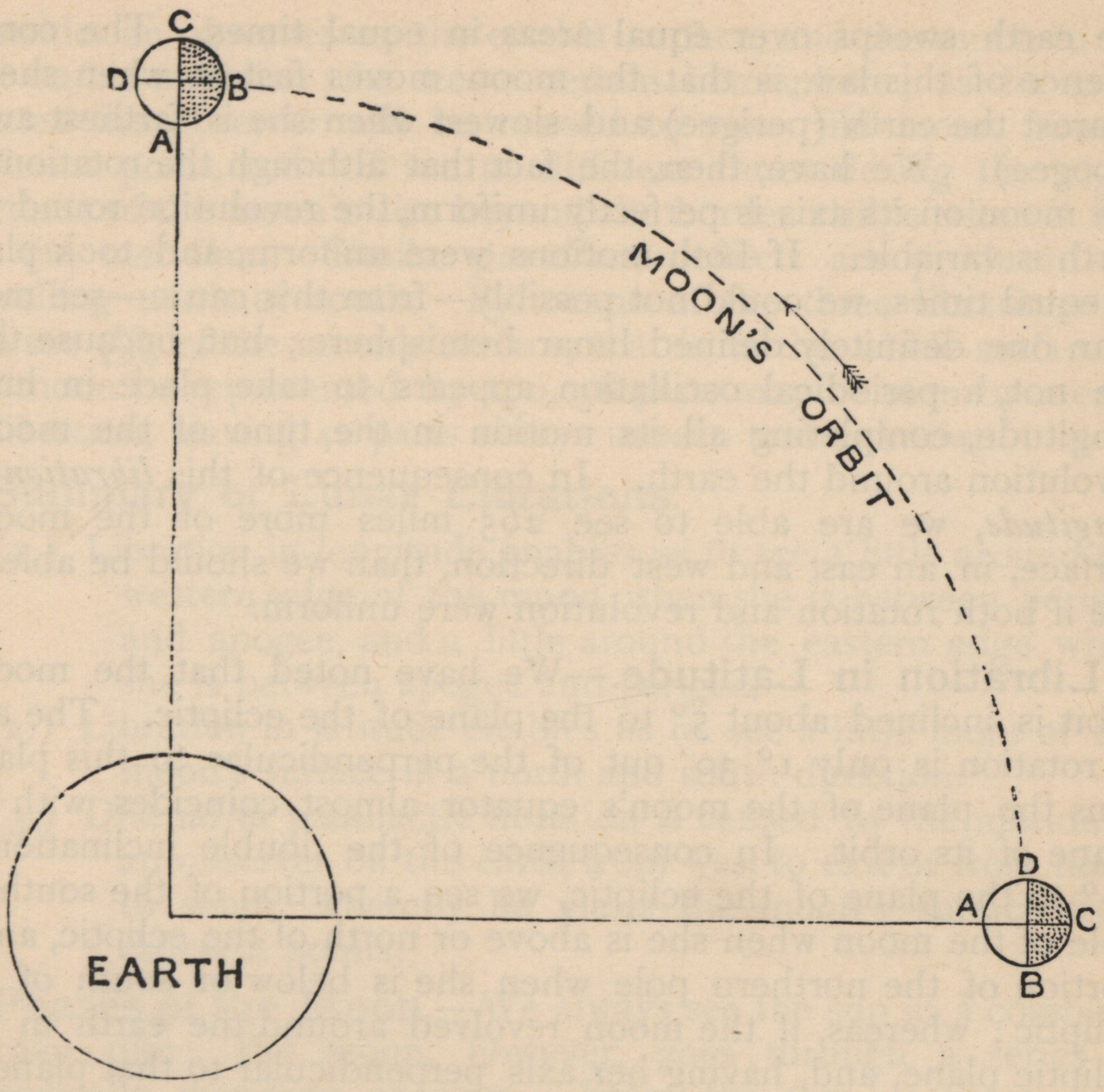


Fig. 54. Showing why we always see the same side of the Moon.

Librations.—It would appear from the preceding paragraph that we cannot possibly see more than one half of the lunar surface; but, as a matter of fact, more than this becomes visible. If a crater is observed exactly on the edge of the moon at a certain time, a series of observations would show that sometimes it appeared right on the edge of the moon and sometimes was removed from it; in fact, the crater would be seen periodically to approach to and recede from the border of the disc. These periodical oscillations whereby we see slightly more than one half of the lunar surface are called librations.

Libration in Longitude.—The second law of planetary motion asserts that the line joining a planet to the sun sweeps over equal areas in equal times; this also applies to the motion of the moon around the earth, and hence the line joining the moon to

the earth sweeps over equal areas in equal times. The consequence of this law is that the moon moves fastest when she is nearest the earth (perigee) and slowest when she is farthest away (apogee). We have, then, the fact that although the rotation of the moon on its axis is perfectly uniform, the revolution round the earth is variable. If both motions were uniform, and took place in equal times, we could not possibly—from this cause—see more than one definitely defined lunar hemisphere; but, because they are not, a periodical oscillation appears to take place in lunar longitude, completing all its motion in the time of the moon's revolution around the earth. In consequence of this *libration in longitude*, we are able to see 265 miles more of the moon's surface, in an east and west direction, than we should be able to see if both rotation and revolution were uniform.

Libration in Latitude.—We have noted that the moon's orbit is inclined about 5° to the plane of the ecliptic. The axis of rotation is only 1° 30′ out of the perpendicular to this plane, thus the plane of the moon's equator almost coincides with the plane of its orbit. In consequence of the double inclination of $6\frac{1}{2}°$ to the plane of the ecliptic, we see a portion of the southern pole of the moon when she is above or north of the ecliptic, and a portion of the northern pole when she is below or south of the ecliptic; whereas, if the moon revolved around the earth in the ecliptic plane, and, having her axis perpendicular to that plane or at a constant angle to it, we should always see the same amount of lunar surface in a north and south direction, and a point on the top or bottom edge of the moon would always be exactly at the top and bottom. The reason of this is easily understood from analogy with the earth. An observer on the sun would sometimes see the earth's north pole and sometimes the south pole, the amount visible varying with the position of the earth in its orbit. This alternate showing of the moon's north and south poles is called the *libration in latitude*, and enables us to see, both north and south, $225\frac{1}{2}$ miles more of the moon's surface than would otherwise be visible. We must add that since libration in longitude and in latitude arise from the motion of the moon itself, they are both independent of the position of the observer on the earth.

Diurnal or Parallactic Libration.—There is yet another of these librations of the visible hemisphere of our satellite; but, unlike the two previous ones, which have a period of a month, this has a daily period, and hence is termed the *diurnal libration*.

Consider an observer on the earth's surface, and the moon to be just on his meridian; he sees a certain hemisphere; as the earth rotates the observer will be caused to view the moon from a different point, and will see at different times during the night portions of the moon's disc beyond the border visible when it was on the meridian. Similar *parallactic* effects are produced by travelling north or south. By means of the three librations we can see $\frac{58}{100}$ of the moon's surface, that is, if the whole surface of the moon be represented by 100, 58 parts may be seen by means of libration, leaving 42 parts always unseen and unknown.

Summary of Lunar Librations.

(1.) Libration in longitude enables us to see a little around the western edge of the moon when she is between perigee and apogee, and a little around the eastern edge when she is between apogee and perigee.

(2.) Libration in latitude enables us to see a little more of the moon's surface in a north and south direction.

(3.) Diurnal or parallactic libration is caused by the motion of an observer on the earth from west to east or from north to south, whereby he views the moon's surface from different points.

Phases of the Moon.—We always see the sun as a complete circular disc; the moon, however, goes through a series of periodically recurring changes. From the thin crescent, seen shortly after new moon, the bright portion of the lunar surface increases in size night by night until half the disc is seen, then full moon occurs, then half moon again, and finally the crescent thins down to invisibility. These changing appearances are called the *phases of the moon*. The light we receive from the planets is reflected sunlight and not due to an appreciable extent to any self luminosity. The moon also shines by reflected sunlight. When the rays of the sun fall upon any opaque body they illuminate it. We sometimes see the walls of houses glaringly bright, but we know that it is only sunlight second-hand. It is the same with the moon; and we have now to explain why, although the sun is always shining on our satellite, we do not always see a fully illumined circular disc.

It has been noted before that the average distance of the moon from the earth is 240,000 miles. The distance of the sun, however, is so great—being nearly 400 times this distance of the moon's—that rays coming from it and falling upon the earth and

moon may all be considered parallel. Let the moon occupy the position opposite the sun as shown on the left of Fig. 55, then, since it is generally above or below the ecliptic, some of the sun's rays passing above or below the earth will strike full upon its surface, and the inhabitants on the dark side of the earth, that is, on the side of the earth turned away from the sun, will see a 'full moon.' When the moon occupies this position with respect to the sun and earth, the rotation of our globe causes it to cross the meridian about midnight. At such times the sun and moon are said to be in opposition.

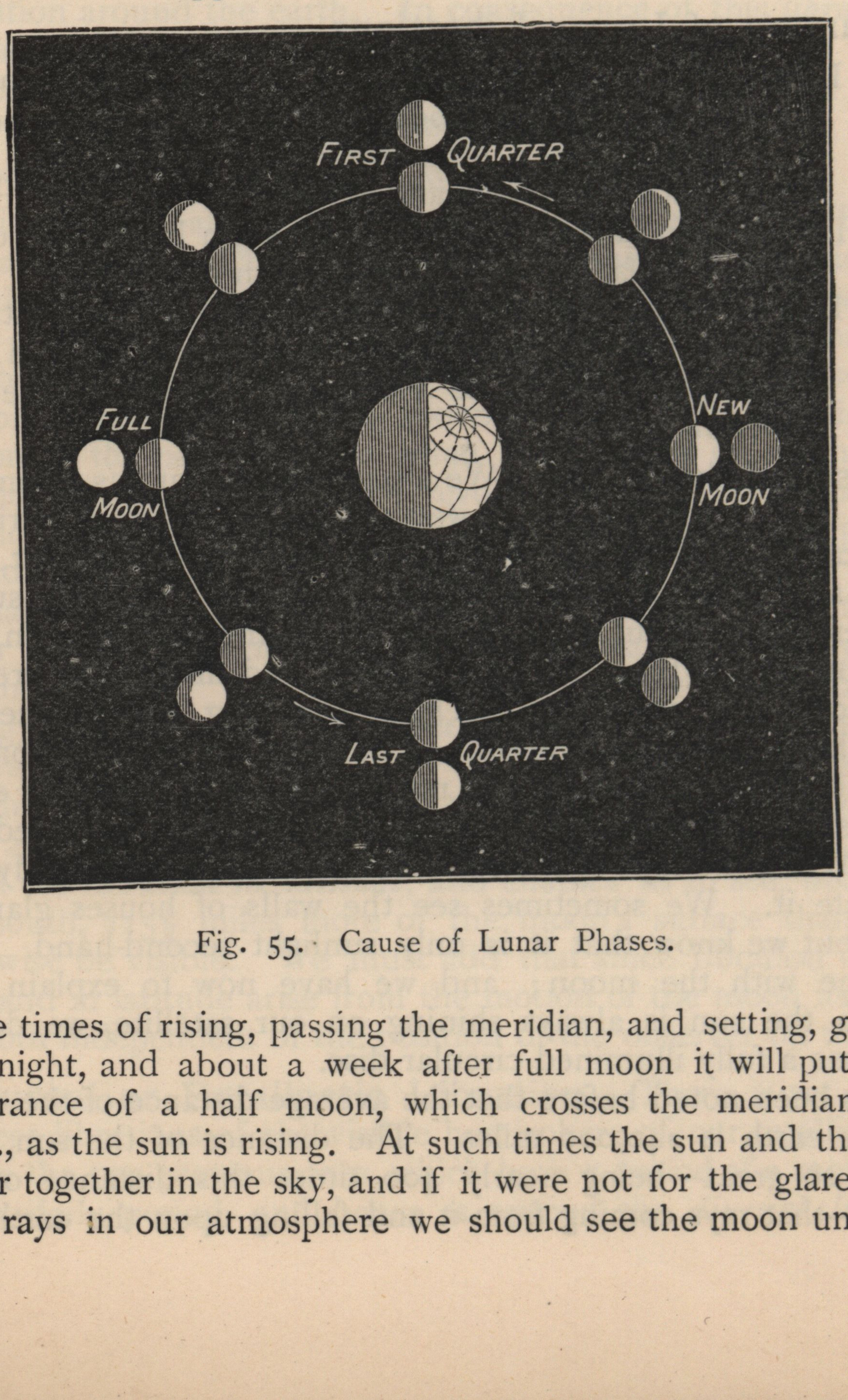


Fig. 55. Cause of Lunar Phases.

The times of rising, passing the meridian, and setting, get later each night, and about a week after full moon it will put on the appearance of a half moon, which crosses the meridian about 6 a.m., as the sun is rising. At such times the sun and the moon appear together in the sky, and if it were not for the glare of the sun's rays in our atmosphere we should see the moon until mid-

day; but we know that as the sun rises in the sky it extinguishes the feeble rays of the moon. From the appearance of half moon more and more of its surface becomes obscured, the visible portion becomes crescent shaped, the interval between its passage across the meridian and the sun's passage is lessened, and our satellite is only seen in the morning shortly before sunrise.

About a fortnight after full moon nothing is seen of it, and the reason is manifestly because, as is shown in the accompanying figure, its dark side is turned towards the earth. A time comes when the sun and moon are in conjunction, that is, they both cross the meridian at the same time, the moon perhaps a few degrees above or below the sun, which is in the ecliptic, but on the same celestial meridian. The moon is said to be new when it is in conjunction with the sun, but it will be understood that at this time it cannot be seen at all. If, about four days after new moon, we watch the sun set in the west, a narrow crescent of light will be observed to set a few hours after it, the horns or cusps of the crescent being turned away and equidistant from the sun. This crescent crosses the meridian a few hours after the sun. Of course, strictly speaking, a crescent is formed as soon as the moon passes conjunction, but twilight renders it invisible until about four days after new moon. The crescent grows day by day, and seven days after new moon the appearance of half moon will again occur; this half moon will cross the meridian six hours after the sun, that is, at 6 p.m. The bright portion of the lunar surface will go on increasing; its times of rising, meridian passage and setting will get later; and on the fourteenth or fifteenth day after new moon the whole disc is again lit up and another full moon occurs, which passes the meridian at midnight.

Summary of Lunar Phases.—To sum up the various phases of the moon, we have:—

An invisible new moon at conjunction.
Crescent-shaped moon, between new moon and half moon, that is, between conjunction and quadrature.
Half moon occurs about seven days after new moon, and our satellite is said to be in the first quarter or at quadrature.
Gibbous moon, between the first quarter and full moon, that is, between quadrature and opposition.
Full moon, about a fortnight after new moon, when it is at opposition.

After the full our satellite again becomes gibbous, then passes half moon or the last quarter, then diminishes to a thin crescent and finally returns to new moon to commence afresh the cycle. A fact which follows upon the various lunar phases is that the two horns of the moon seen before the first and after the last quarter must always be equidistant from the sun, and turned away from it. No matter where the moon is in her orbit, the line of greatest width must point to the sun.

Illustration of Lunar Phases.—In order to clearly understand why the moon should go through all these changes, although the sun lights up a whole hemisphere, the student is recommended to get a ball of some kind and paint half of it white. If this ball be carried around the student with its painted face always turned in a fixed direction, it will be observed that sometimes the full painted surface is seen, sometimes half, and sometimes none at all. This is exactly analogous to what happens in the case of the moon; the rays of the sun fall upon our satellite and always illuminate the half facing it. The bright portion is always on the side near the sun, but though the rest is not bright it still exists. We do not, however, always see this fully illumined disc, but various portions of it depending upon the relative position of the earth and moon.

Earth-Shine.—When the moon is near conjunction and her crescent is small, a faint ashy light is seen to illuminate the whole hemisphere, the bright crescent appearing part of a somewhat larger disc than the dark portion. This appearance is commonly known as 'the old moon in the young moon's arms.' Its cause will be understood from the figure showing the moon's phases. It will be seen that when the moon is near conjunction the light of the sun is reflected from the earth and illuminates its whole hemisphere. Indeed, an observer on the moon would see the earth go through exactly the same phases as we do the moon, but in a reversed order, so that when it is new moon with us it is *full earth*, so to speak, to an observer on this side of the moon. The bright crescent appears larger than the other portion of the moon because of the optical effect called *irradiation*, that is, a white or bright body always appears larger than a dark one of the same size.

The Moon's Light.—The amount of light given to the earth by the moon is very small compared with that of the sun, careful



Fig. 56. A Lunar Landscape lit up by light reflected from the Earth.

determinations showing that the sun gives us about 620,000 times as much light as the full moon. On this estimate, if the sky were lined with full moons, we should only receive about one-ninth the quantity of light that reaches us from the sun.

The Harvest Moon. — Near the time of the autumnal equinox, the moon rises at very nearly the same time for several nights, instead of rising about an hour later. In consequence of this, the duration of moonlight is increased and the full moon, which occurs near September 23, is called the harvest moon. The phenomenon is caused by the inclination of the orbit of the moon to the equator. If the moon moved in the plane of the equator she would rise 51 minutes later every night. But her distance from the equator varies from $18\frac{1}{2}°$ to $28\frac{1}{2}°$, that is, the moon may be this amount above or below the equator. The result is that the moon rises and describes paths differently inclined to the horizon throughout the month, for the inclination of the equator to the horizon is constant. Now the time taken for an arc of the moon's path to appear above the horizon depends upon its inclination to the horizon. It is least when the inclination is least and *vice versa*. In every month, therefore, the moon appears to rise at about the same time for several nights owing to the small inclination. When the full moon does this, as at the time of the autumnal equinox, particular attention is attracted to the circumstance, and we get the harvest moon.

Shadows.—If an opaque ball is held in front of any source of light, we know by common experience that it will cast a shadow; this shadow is made up of two portions—one dark central part called the *umbra*, and a less dark part surrounding it called the *penumbra* or part shadow. The sun is a source of light, and our

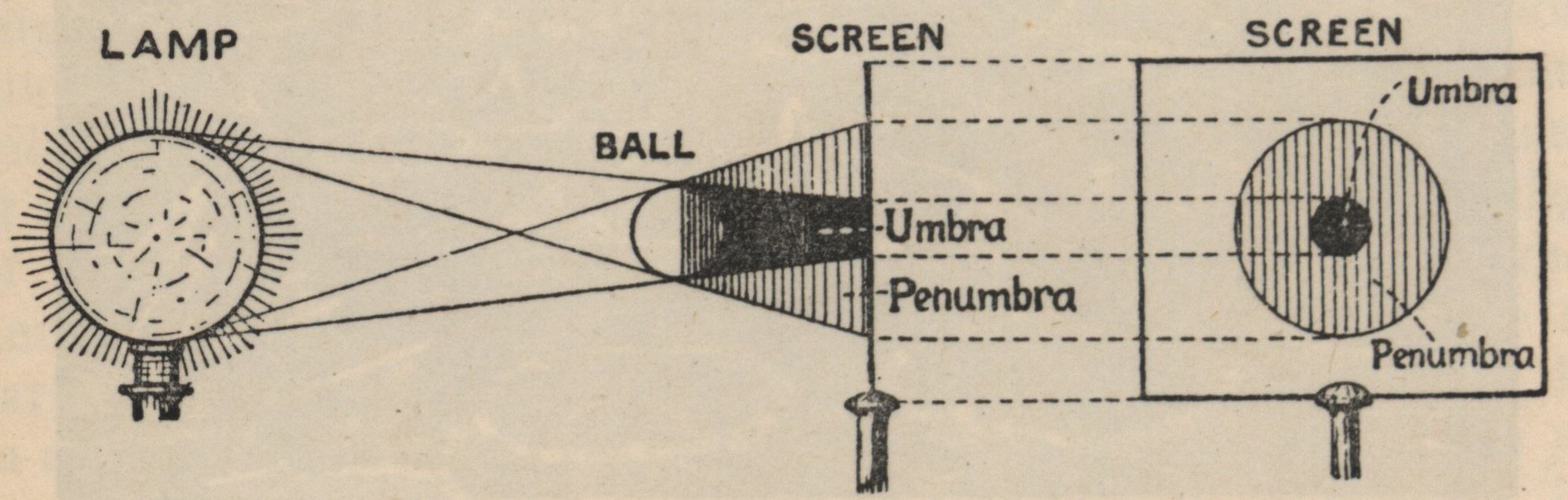


Fig. 57. Parts of a Shadow.

earth is an opaque sphere; hence, since the earth is always in the sun's rays, it is always casting a shadow. This shadow will have the conical form shown in Fig. 57, the black portion indicating the umbra and the outer portion the penumbra.

Lunar Eclipses.—It occasionally happens that at the time of full moon part or the whole of its disc becomes obscured. A dark shadow, having a circular outline, first appears on the eastern edge, slowly passes over, sometimes blotting out entirely the light of our satellite, and then leaves at the western edge. Thus the eastern edge becomes first obscured and is the first part to become visible after obscuration. These appearances are called eclipses of the moon. The fact that such eclipses always occur at full moon was early noticed, and the idea that the cause of an eclipse was the moon passing into a shadow cast by the earth suggested itself, and was understood by the earliest observers. We are now in a position to investigate the cause more closely.

Cause of a Lunar Eclipse.—We have before noted that the plane of the earth's revolution around the sun is the plane of the ecliptic, hence a line joining the centres of the earth and sun and the apex of the umbra must lie in that plane. It is evident, therefore, that if the moon moved around the earth in the plane of the ecliptic, it would always pass into the earth's shadow at opposition, that is, at full moon, and we should never see a full moon. But we know that the moon's orbit is inclined a little more than 5° to the ecliptic plane, hence, at opposition, she may

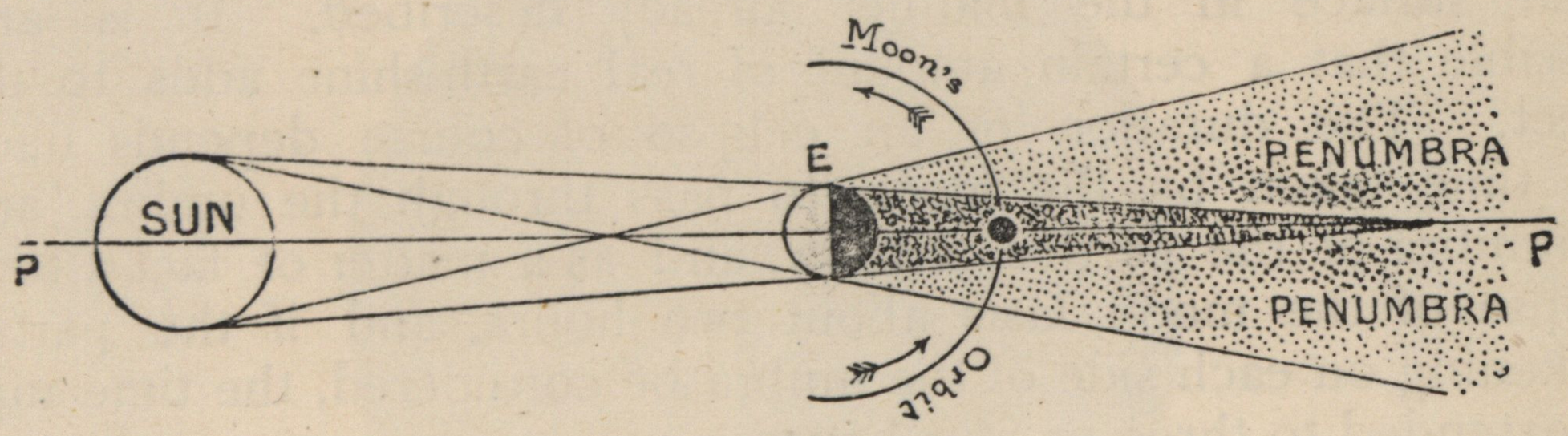


Fig. 58. Cause of Lunar Eclipse.

be any distance from 0° to 5° either above or below the ecliptic, and therefore any distance from 0° to 5° above or below the apex of the conical shadow cast by the earth. Twice in every month the moon is at a node, that is, at one of those points where the plane of its orbit intersects the ecliptic plane, and if it is either 'new' or 'full' at such times an eclipse must occur. When, therefore, the sun, earth, and moon are exactly in the same straight line, the moon passes through the earth's shadow, and is eclipsed (Fig. 58).

Phenomena of Lunar Eclipses.—Eclipses of the moon are of two kinds; total, in which case she is totally immersed in the earth's shadow, so that no direct sunlight can reach her; and partial, when the moon is only partially immersed in the earth's shadow. In order that a total eclipse of the moon may happen, our satellite must be at one of the points where its orbit intersects the ecliptic. If she is not exactly at one of these points a partial eclipse may only occur, because then only a portion of the upper or lower limb passes through the earth's shadow. When a total eclipse of the moon occurs, the eastern limb comes in first contact with the penumbra of the earth's shadow. This effect, however, is barely perceptible to the naked eye, and little loss of light is noticed until the umbra is reached, when the eastern edge becomes almost invisible, the circular shadow encroaches slowly upon the bright lunar surface and totally eclipses it for about two hours. After this the shadow is seen to pass off at the western edge of the moon. It is noticed that during a lunar eclipse a coppery-coloured light appears to illuminate the moon. If the earth had no atmosphere surrounding it, this would not happen; the explanation of the phenomenon being that the sun's rays which pass near to the earth are bent or refracted by its atmosphere into the cone which forms the shadow, thus illuminating the lunar surface in the manner already described. It is also possible that a certain amount of real earth-shine adds to the effect. The duration of an eclipse of course depends upon the time taken by the moon to pass through the umbra and penumbra of the earth's shadow, and as a matter of fact a total eclipse of the moon lasts about two hours, and if the partial darkening on each side of the umbra be considered, the time may be extended to three or four hours.

Cause of a Solar Eclipse.—Besides the darkening of the full moon, called an eclipse of the moon, the light of the sun is sometimes cut off. A dark shadow meets the western edge of our

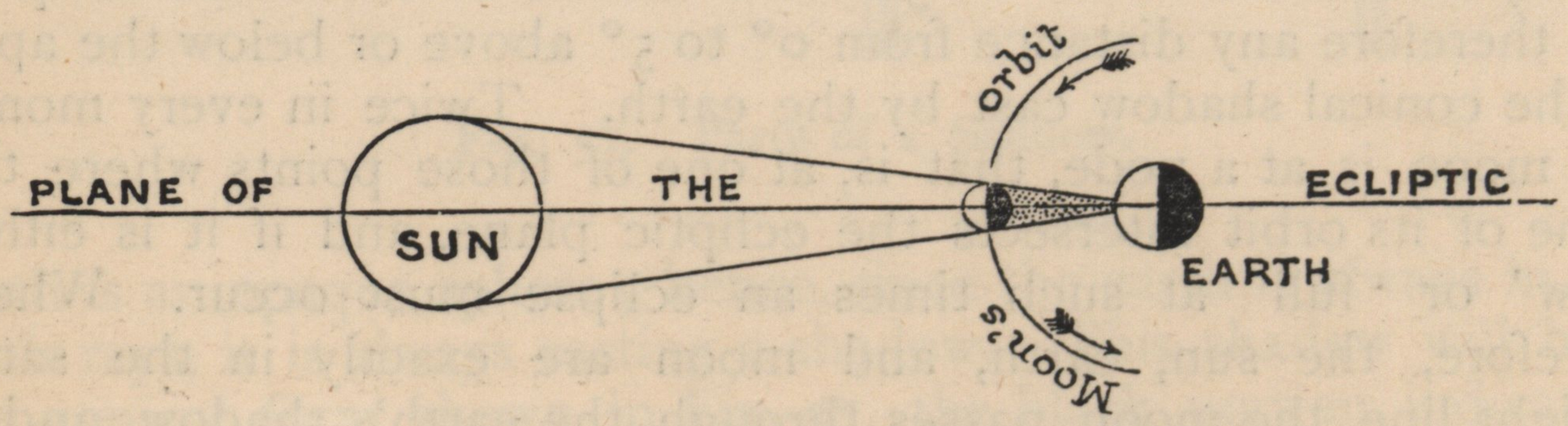


Fig. 59. Cause of an Eclipse of the Sun.

luminary, passes over its disc, and totally eclipses it, it may be for seven minutes, it may be for a few seconds. This appearance is called an eclipse of the sun, or a solar eclipse.

Lunar eclipses are caused by the earth coming between the sun and moon, and occur at opposition, that is, at full moon. Solar eclipses are caused by the moon coming between the earth and the sun, and occur at conjunction, that is, at new moon. If the moon's orbit coincided with the ecliptic, a solar eclipse would happen every new moon, but as the orbit is inclined about 5° to the ecliptic, the moon sometimes passes above and sometimes below the line joining the centres of the sun and earth, and so her shadow does not touch the earth. A diagrammatic representation of a solar eclipse is shown in Fig. 59.

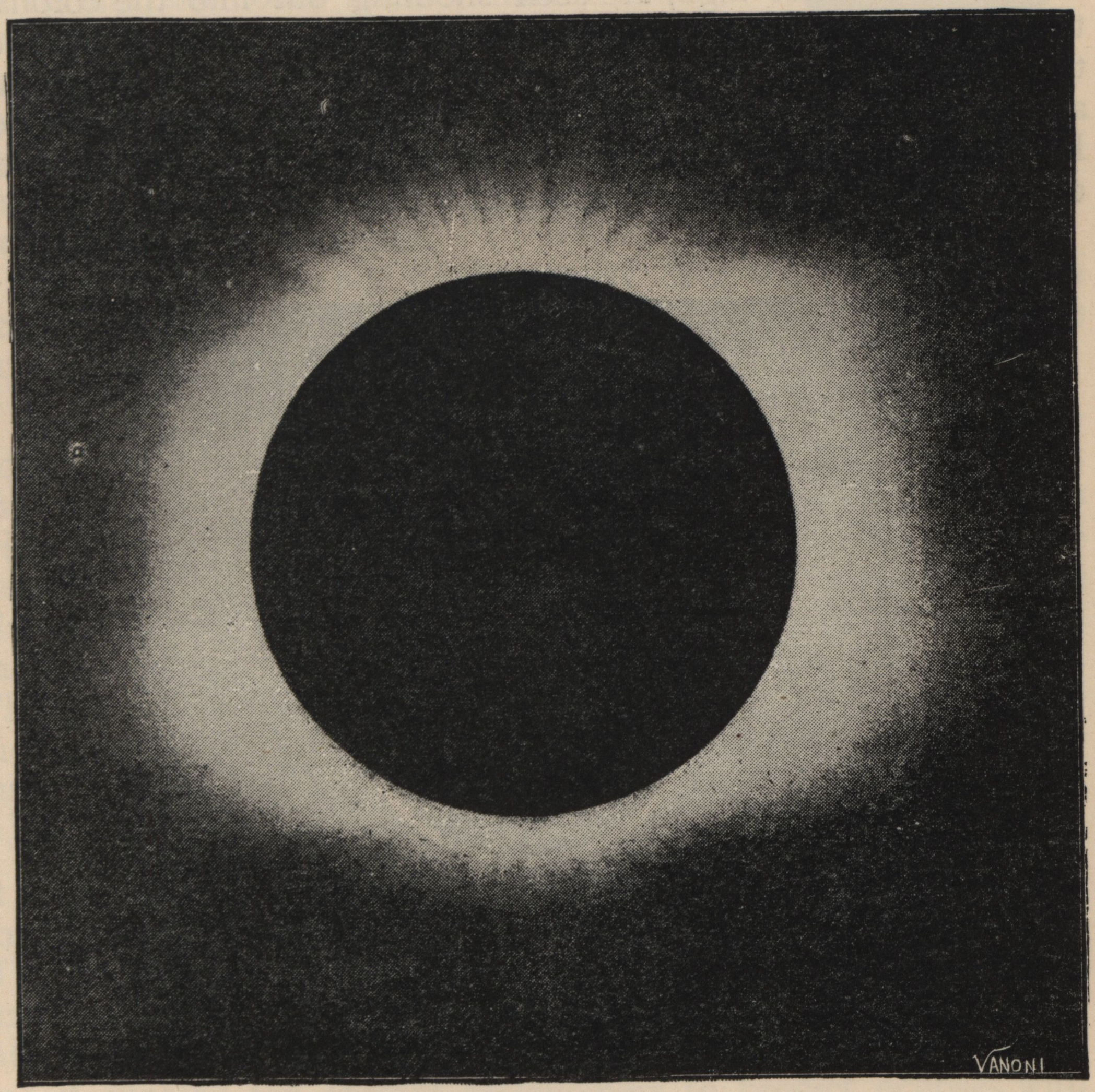


Fig. 60. The Corona of January 1st, 1889.
(*From a Photograph by Professors Pickering & Barnard.*)

Phenomena of Total Solar Eclipses.—Solar eclipses are of three kinds, total, annular, and partial, and it is evident from an inspection of the accompanying figure, that a total eclipse can only occur when the observer is near the line joining the centres of the sun and moon; indeed, the breadth of this space traced upon our globe by the lunar umbra never exceeds 180 miles. An observer situated within this belt sees a dark shadow cross the sun from west to east, eclipsing it totally for a short time. As the sun's light is shut off by the moon's shadow, the stars are seen to come out and a halo or corona appears to surround the lunar disc (Fig. 60). This halo belongs to the sun and is invisible under ordinary circumstances because of the dispersive action of the earth's atmosphere. During totality red flames called prominences, many thousands of miles high, are seen shooting out into the corona; these also are invisible under ordinary circumstances because of the glare of sunlight in our atmosphere. By an ingenious arrangement, however, discovered independently by Professor Lockyer and M. Janssen in 1868, prominences may now be detected and their heights measured without an eclipse.

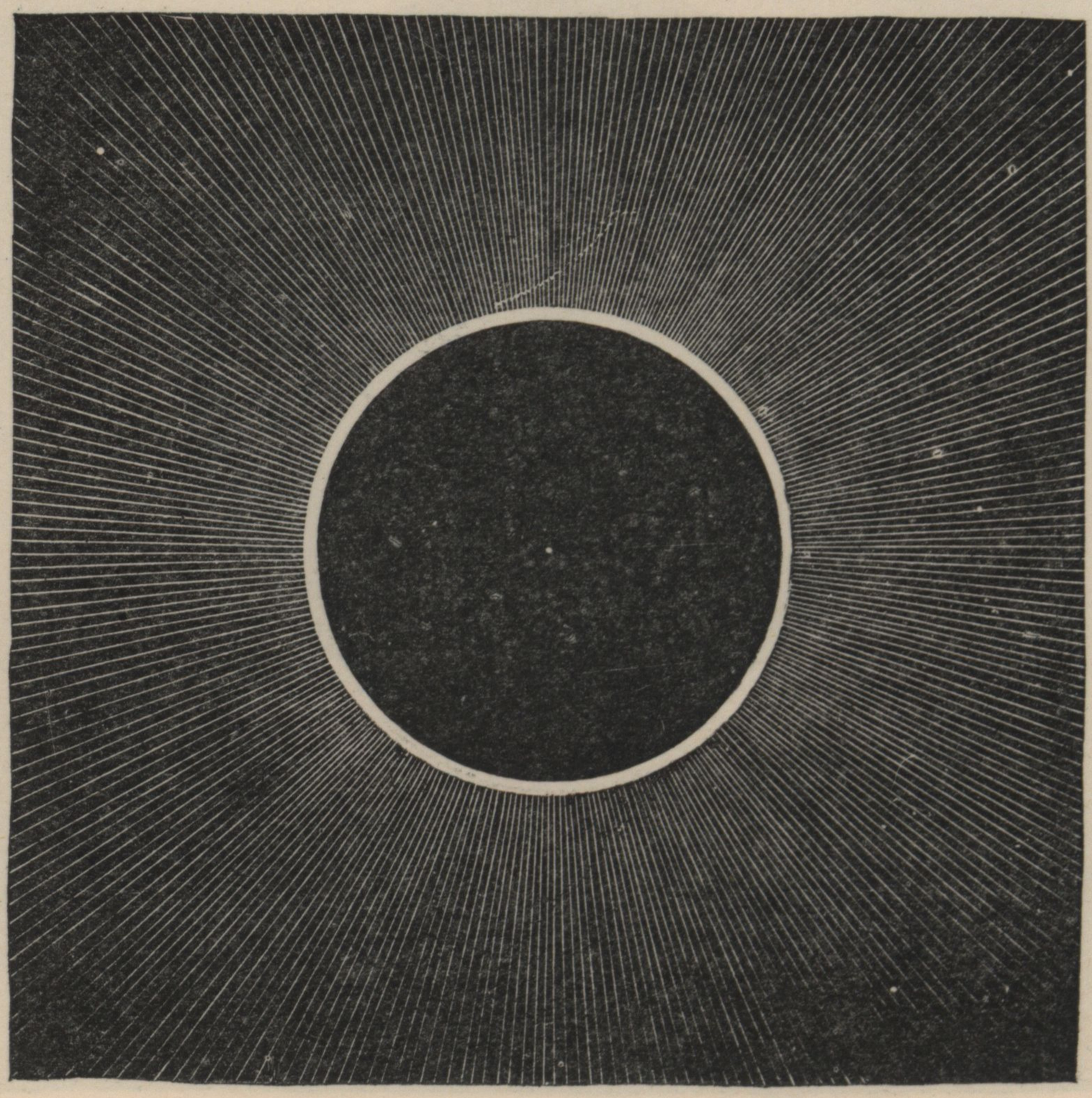


Fig. 61. Annular Eclipse of the Sun.

Annular and Partial Solar Eclipses.—If the moon passes exactly between the earth and the sun, as in a total eclipse, and the apparent diameter of the moon is less than that of the sun, it is evident that the whole of the sun's disc cannot be covered, and a ring of light will surround the dark shadow. This is called an annular, that is ring-shaped, eclipse (Fig. 61). We have shown that the moon's orbit is an ellipse and has a point of nearest approach to the earth (perigee), and a point of greatest distance (apogee). It is to this fact that we have to refer the cause of annular eclipses. When the moon is farthest from the earth her shadow is not long enough to reach the earth and she looks smaller than the sun, hence an observer situated in a line with the centre of the shadow sees a ring of light surrounding it. An annular eclipse of the moon is impossible, because the earth's shadow where the moon cuts it always exceeds the lunar diameter.

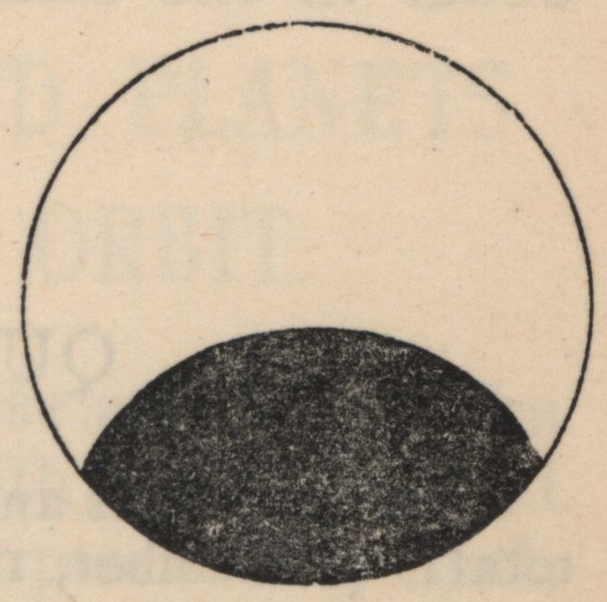


Fig. 62.
Partial Eclipse of the Sun.

If the moon does not pass centrally over the sun's disc then only a portion of the latter is covered up and a partial eclipse occurs (Fig. 62).

Relative Frequency of Solar and Lunar Eclipses.—Solar eclipses are really more frequent than lunar eclipses, but they are only visible over a strip on the earth about 200 miles wide. On the other hand, lunar eclipses are visible over a whole hemisphere of the earth, hence they are more usual at any one place than eclipses of the sun. It is interesting to note that there cannot be more than seven eclipses in a year nor less than one. There may be three lunar eclipses in a year but no more, and there may be none. The average number of eclipses is four, two lunar and two solar.

The Saros.—An eclipse can only happen when the moon is at a node, and, since the nodes are themselves in revolution, the conditions are constantly changing. By a long series of observations of eclipses the Chaldeans and Egyptians discovered that eclipses occurred in the same order after a period of 223 lunations, or rather more than 18 years. This cycle was called the Saros, and it enabled the ancient astronomers to predict eclipses with a fair amount of accuracy. For if an eclipse happened at any

time, then after 223 lunations it would be repeated. The reason of this will be understood from what has previously been said with regard to the movement of the line of nodes. When the nodes have made nineteen synodic revolutions, the moon has made exactly 223 synodic revolutions, so the original conditions are again fulfilled, that is to say, the moon is brought back to the same position with respect to her nodes and the sun, and eclipses occur in the same order.

QUESTIONS ON CHAPTER VI.

1. What causes an eclipse of the moon? Why are not such eclipses always total? (December, 1884.)

2. Draw a diagram explaining the phase of the moon. (December, 1882.)

3. Write down what you would say, and give the diagrams you would make in explaining the phases of the moon. (December, 1880.)

4. Show, by means of a diagram, the relative positions of the sun, moon, and earth at 'new' and 'full' moon.

5. Explain briefly the terms 'inferior planet,' 'phases of the moon,' 'perigee,' 'morning star,' 'neap tides,' and draw diagrams illustrating the second and last.

6. Explain the terms in *italics* in the following passage:—'In the year 1886 there will be a *total eclipse* of the sun on August 29th, invisible at Greenwich. Begins at 10h. 19m. a.m. (Greenwich Mean Time) in *long.* 66° 24′ W. and *lat.* 11° 55′ N. The *central eclipse* begins at 11h. 14m. a.m. in long. 79° 46′ W. and lat. 9° 48′ N.' What part of the British Empire would be a favourable position for observing this eclipse? What is the object of sending out an 'eclipse expedition'?

7. Define synodic and sidereal revolution, and give the lengths of the synodic and sidereal months.

8. Describe the changes which take place in the directions of the line of nodes and line of apsides.

9. Explain fully why the sidereal month is shorter than the synodic month.

10. How is it that only one side of the moon is seen?

11. What are librations of the moon?

12. What are the chief phenomena observed during total eclipses of the sun and moon?

CHAPTER VII.

ACTION OF THE SUN, MOON, AND PLANETS UPON THE EARTH AND ITS ORBIT.

It was remarked in very early times that the rise and fall of the waters of the sea were in some way connected with the moon, and the exact connection will be described in this chapter. The earth is subject to other disturbances owing to the constantly varying attractions of the members of the solar system. The planets tend to give the orbit of the earth—the plane of the ecliptic—a different position; the sun and moon tend to pull the plane of the earth's equator into the level of the ecliptic, and the result of their action is that the equator slowly turns round, while the obliquity of the ecliptic is not affected. These and other similar irregularities are known in astronomy as *perturbations*, and are said to be *secular* because they take a long time to manifest themselves. The relation that exists between the moon and the tides is capable of easy demonstration, but the cause of secular variations is often much more complicated. We will begin the chapter with a statement of obvious phenomena and this will lead the way to a description of effects not so readily noticed.

Tidal Phenomena.—Almost all the inhabitants of a maritime country like Great Britain have observed the constant and regular rising and falling of the waters of the sea, known as tides. For about six hours the sea slowly rises, then falls—to rise and fall again, thus reaching the highest and lowest points twice in a day. When the highest point is reached, *high-water* is said to occur, while the lower level is termed *low-water*. A tide *flows*, or is a *flood* tide, when the water is rising, and *ebbs* when it is falling.

The Moon and Tides.—It was noticed at a very early period of human history, that a connection existed between the tides and the motion of the moon, and the fact that high tides always occur when the moon is in a certain part of the heavens

made it very manifest that they were due to lunar influence. Hence it is that vague notions have always filled the minds of men as to the nature of the disturbing influence; but it was left to Newton to demonstrate the true cause of the phenomenon.

The moon rises, passes the meridian, and sets fifty minutes later every day. Similarly, the times of high and low water are fifty minutes later on an average every day. Or, to put it in another way, the average interval between two successive passages of the moon across the meridian is 24 hrs. 51 mins. Sometimes it is more, sometimes less, but this is the length of the average or mean lunar day. In like manner, the average interval between alternate high or low water is also 24 hrs. 51 mins. In this interval two high and two low tides occur, so that high and low water occur when the moon is not visible; hence the explanation that tides are produced by the attraction by the moon of the water under it is not sufficient, for, if such were the case, only one tide a day would occur.

The Moon's Action on the Waters of the Earth.—We will give the theory of tides worked out by Newton—now called the statical theory—and show that it is sufficient to explain

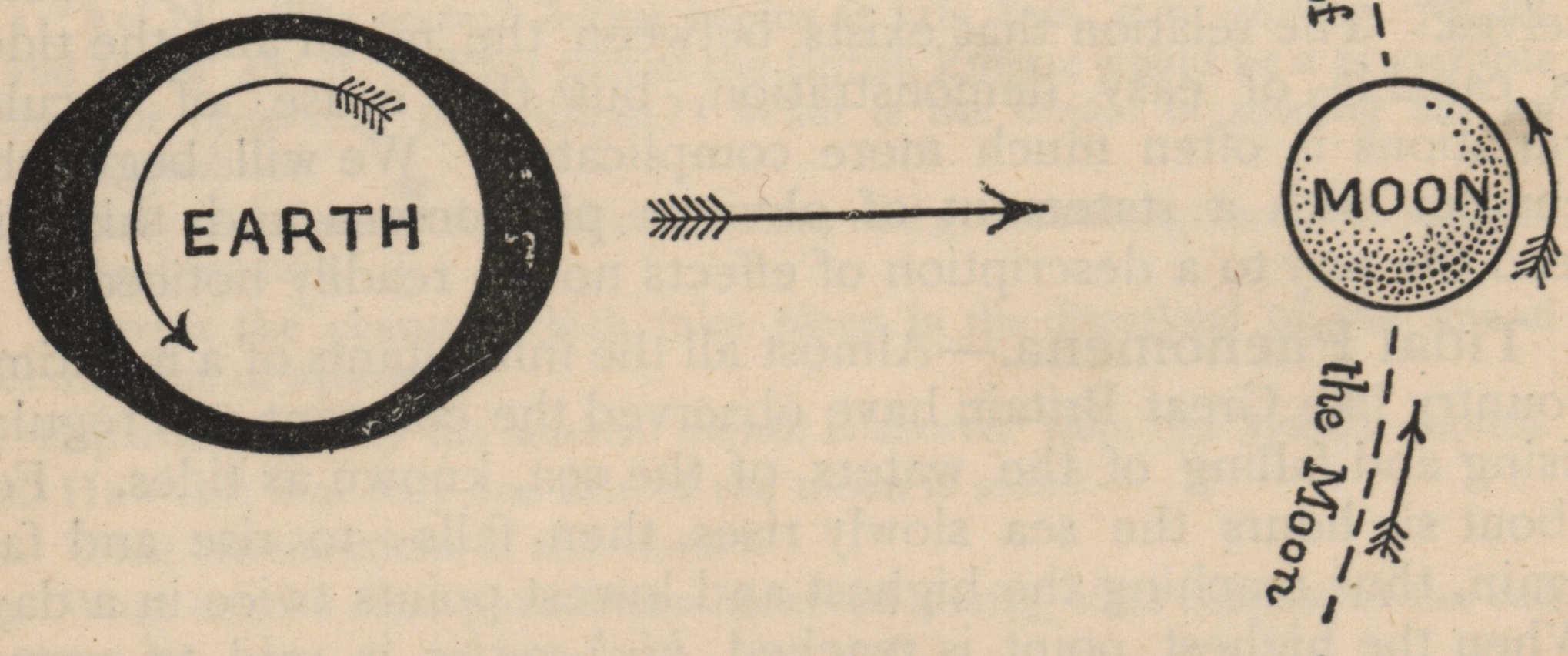


Fig. 63. Theoretical effect of the Moon's attraction upon the waters of the Earth.

the most prominent phenomena. Consider the earth at rest and the moon to occupy her position relative to it, that is, 240,000 miles away. Now the force of gravitation varies 'inversely as the square of the distance' between the attracting bodies; hence

if the distance of the moon from the earth were doubled the attraction between the two bodies would be $\frac{1}{4}$ of what it is at present; if the distance were trebled the force would have $\frac{1}{9}$th of its present value. From this law it is evident that the effect of the moon's attraction upon the side of the earth near it is greater than the attraction at the earth's centre, and the effect in the case we are considering is that the waters are pulled away from the solid earth and heaped up under the moon into a mass having a spheroidal form (Fig. 63). Similarly, the centre of the earth is nearer the moon than the waters on the further side, hence the solid earth is drawn towards the moon with a stronger force than the waters on the side away from the moon are, and the effect is to leave the latter on the opposite side bulged out in exactly the same way as the waters on the side nearest the moon. If the earth were at rest this lemon-shaped projection would travel round our globe with the moon; high water would always occur exactly under the moon and 180° from it, and low water at all places half-way between the two, that is, 90° from either.

Differential Action.—At first sight it would appear that the sun's enormous mass ought to have a much greater effect in causing tides than that incomparably much smaller body, the moon, and we have now to show why this is not the case. The radius of the earth is about 4,000 miles long, the average distance of the moon 240,000 miles, hence it would take 240,000 ÷ 4,000, or 60 times the earth's radius, to reach to our satellite. For convenience, we will take the average distance of the sun as 96,000,000; this in terms of the earth's radius is $\frac{96000000}{4000} =$ 24,000. So that in the case of the moon the radius of the earth is $\frac{1}{60}$ of the distance between it and the earth, whilst in the case of the sun it is only $\frac{1}{24000}$ part of the whole. It is evident, therefore, that the difference of attraction upon the earth's surface and centre, which we have stated to be the cause of tides, is much greater in the case of the moon than in the case of the sun, and hence the tidal effect of the moon is greater than that of the sun.

The student should guard himself against thinking that the moon's tidal effect is greater than the sun's because the former body is nearer the earth, for if the effect simply depended upon distance the sun would predominate. It is the *differential attraction* of the sun and moon upon the earth's centre and the waters at the surface that is the cause of tides. The sun really

exerts an attracting force upon the earth as a whole which is 200 times greater than the force exerted by the moon; its power of raising tides, however, is only about $\frac{2}{5}$ that of the moon. To make this clear conceive our globe covered with water; then the difference of level of the water under the moon and 90° from it would be 2 feet, owing to the attraction of the moon. If the sun only acted it would produce a difference of level of about $9\frac{3}{4}$ inches. Thus the moon's tide is 24 inches, and the sun's tide is $9\frac{3}{4}$ inches; therefore the action of the moon in producing tides is to the action of the sun in producing tides as 24 is to $9\frac{3}{4}$, that is, nearly as 5 is to 2.

The differential actions of the sun and moon can be accurately compared in the following manner:—

Distance of sun = 23,142 times the radius of the earth.
Distance of moon = 60 times the radius of the earth.
Mass of sun = 332,000 times the mass of the earth.
Mass of moon = 0·0125 of the mass of the earth.

$$\text{Thus differential attraction of sun (S)} = \frac{332{,}000}{(23{,}141)^2} - \frac{332{,}000}{(23{,}143)^2}$$

$$\text{And differential attraction of moon (M)} = \frac{0{\cdot}0125}{(59)^2} - \frac{0{\cdot}0125}{(61)^2}$$

$$\text{Hence, S : M :: } \left(\frac{332{,}000}{(23{,}141)^2} - \frac{332{,}000}{(23{,}143)^2}\right) : \left(\frac{0{\cdot}0125}{(59)^2} - \frac{0{\cdot}0125}{(61)^2}\right)$$

From this we find—

Sun's effect : Moon's effect :: 2 : 5.

Spring and Neap Tides.—In a lunar month, two very high and two very low tides occur, separated by a fortnight. The highest tides of the month happen at or near the times of new and full moon, and are termed 'spring tides;' the lowest tides of the month take place when the moon is in her quarters, and are known as 'neap tides.' From what has been previously said, it will be understood that if the sun and moon pull together and their two tides are added, an unusually high tide must occur; similarly, if they act against each other, the high tide must be lower than the average. The times at which the sun and moon act together are represented in Fig. 64. The moon is there shown in two positions in its orbit. When it is new moon, the effect of the sun in producing tides is added to the lunar effect; similarly, when the moon arrives at the position of full moon, the solar and lunar influences

are added together. When, however, the moon is in quadrature, as shown in Fig 65, it is acting against the sun. We know that if the moon existed alone there would be a difference of level of two feet in the water under it and 90 degrees from it. But the sun is also exerting an effect and its tide is partially filling up the

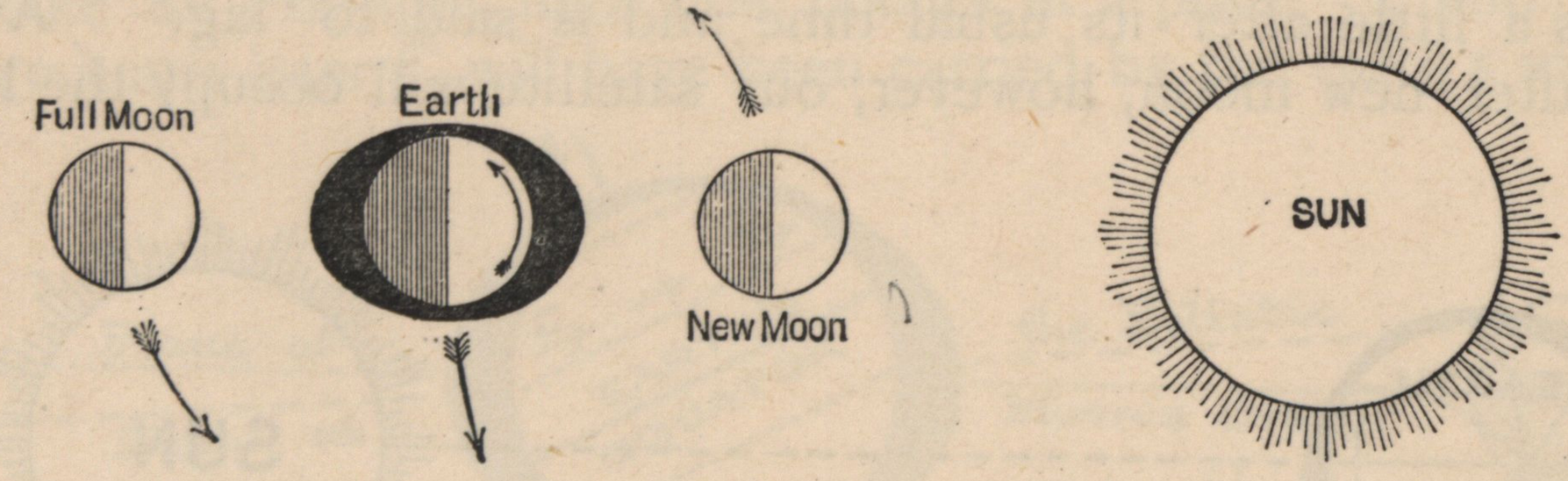


Fig. 64. Relative positions of the Sun, Moon, and Earth at the time of Spring tides.

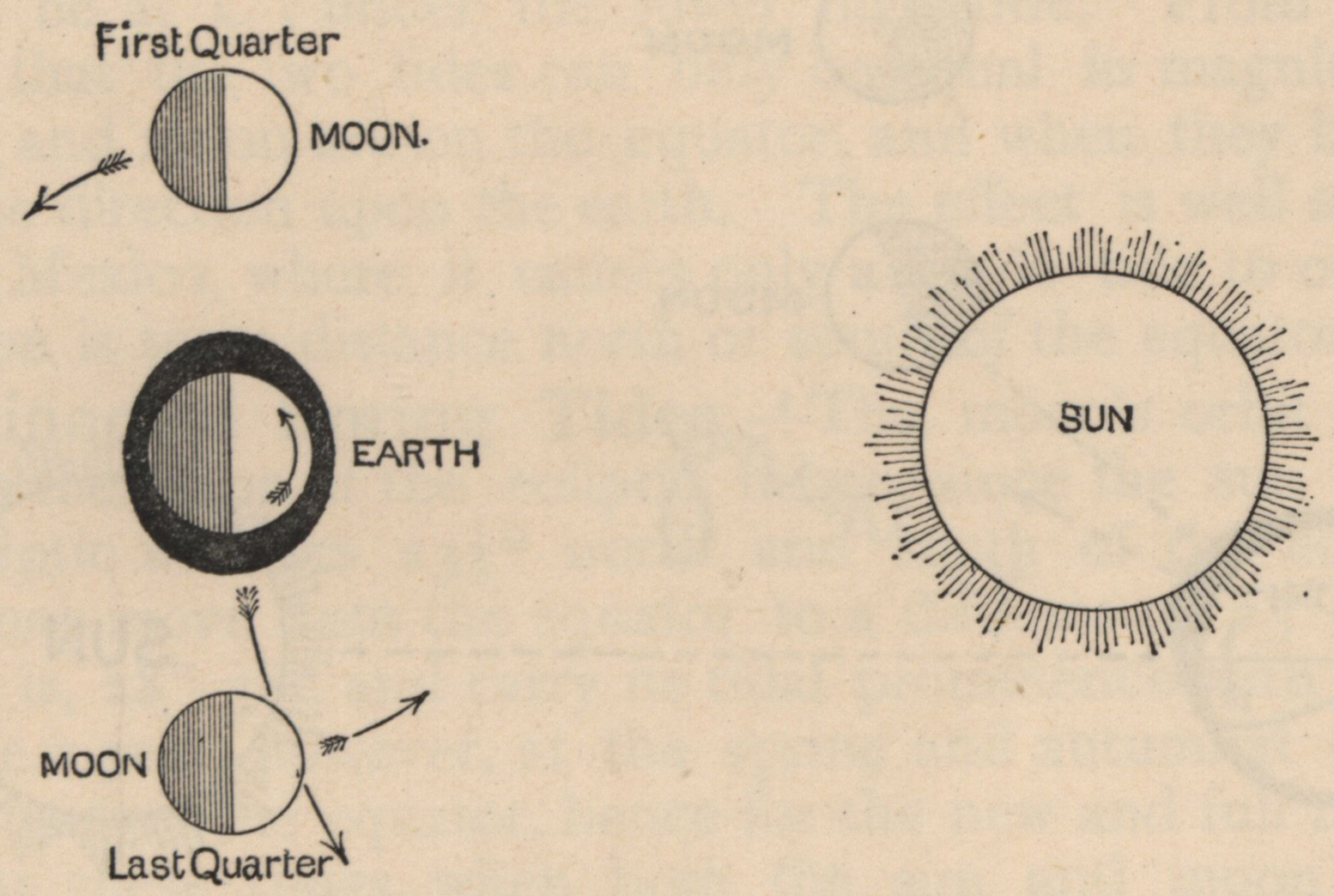


Fig. 65. Cause of Neap Tides.

depression due to the moon's action. The lunar tide, however, being greater than the solar tide, preponderates, and a low 'high water' occurs under the moon. The difference between spring and neap tides can be expressed numerically as follows :—

Spring tides = Moon + Sun = 5 + 2 = 7
Neap tides = Moon − Sun = 5 − 2 = 3

Therefore,

Average Spring tide : Average Neap tide :: 7 : 3

Priming and Lagging of Tides.—It would appear that the interval between two tides should always be 24 hours 51 mins.; this, however, is not the case. When the moon occupies the upper position shown in Fig. 66 the heap of water will not be exactly under it, but, because of the sun's attraction, will assume the form indicated. In such cases, that is before new moon, high water occurs a little after its usual time and is said to 'lag.' A few days after new moon, however, our satellite will occupy the lower

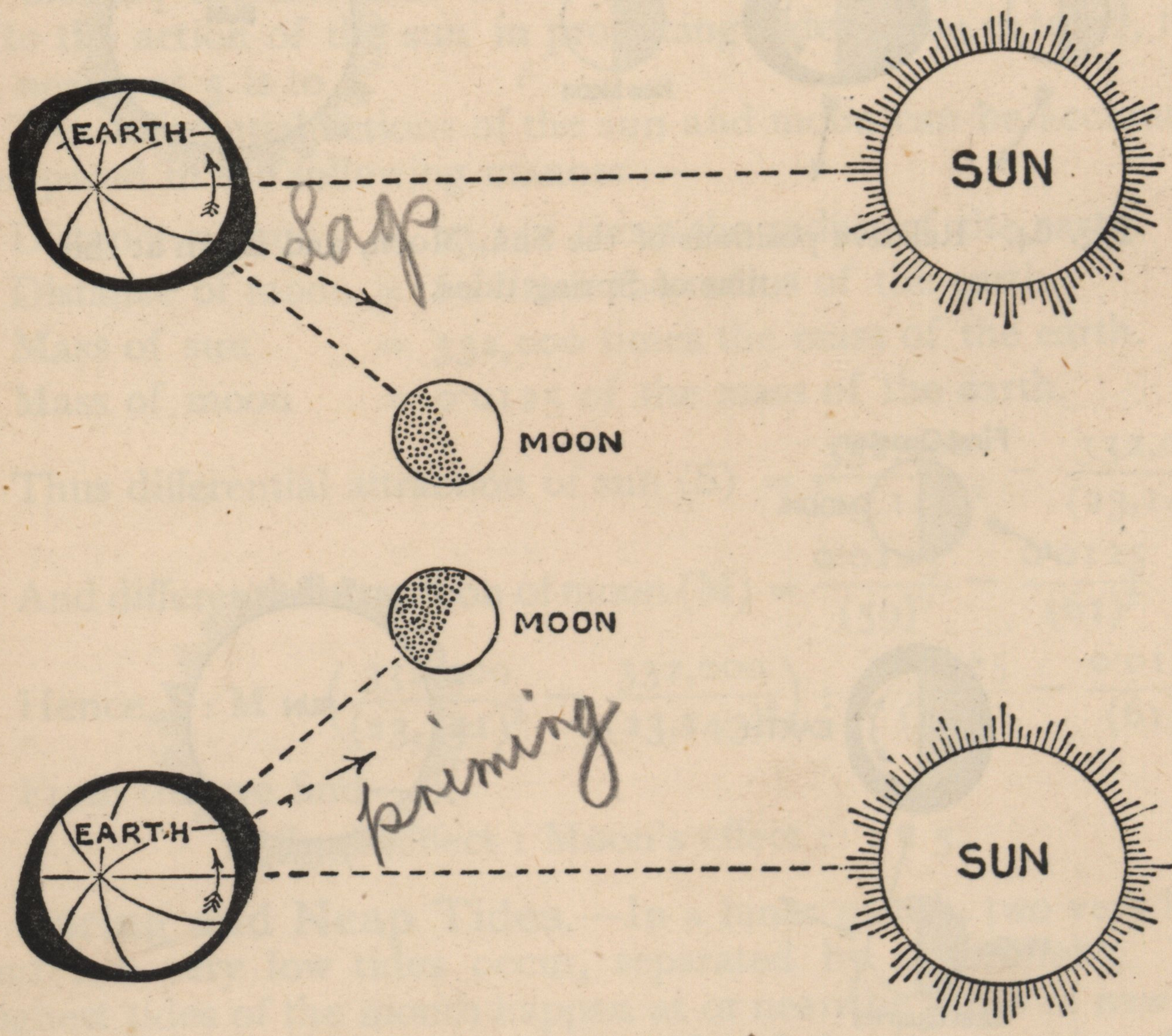


Fig. 66. Cause of Priming and Lagging of Tides.

position in the figure, and high water will occur a little earlier than usual—the tides 'prime.' In a like manner the same effect will occur shortly before and after full moon. We have said that the average interval between the corresponding tides of successive days is 24 hrs. 51 mins., but the lagging and priming each make a difference of about 13 minutes in the tidal interval, so that at the time of priming the interval may only be 24 hrs. 38 mins. and at the time of lagging may be as much as 25 hrs. 4 mins.

Diurnal Inequality of Tides.—Observations show that the two tides of the day are not equal, but differ in magnitude. Diurnal or daily inequality is the term given to this variation. The cause of the inequality is manifest from Fig. 67. The moon in a month moves from about 5° below to 5° above the ecliptic, hence the tidal prominence will move continually over different latitudes. To take an example, high tide occurs at a place C, and about twelve hours later C will have been carried by the earth's rotation

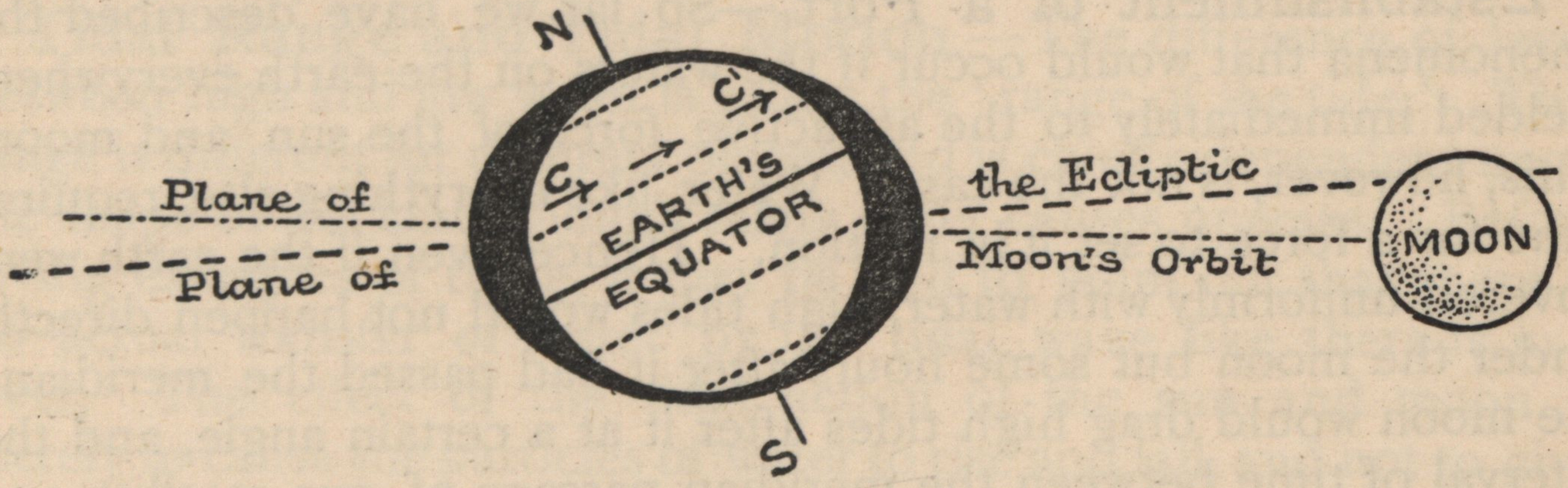


Fig. 67. Diurnal Inequality of the Tides.

so as to be at C′, under the lower high tide. From this it is evident that the two tides can only be equal in magnitude when the sun and moon are on the equator, and when they both act in the same direction upon the earth. The effect is well seen in the Gulf of Mexico, where it causes only a single tide to occur when the moon is some distance north or south of the equator.

Equinoctial Spring Tides.—The moon's orbit is inclined 5° 8′ to the plane of the ecliptic, hence, since the sun moving in the ecliptic wanders $23\frac{1}{2}°$ north and south of the equator, the moon may move from the equator to a distance of 23° 30′ + 5° 8′, that is, 28° 38′, and carry its tidal prominence with it.

Twice a year, however, at the spring and autumnal equinoxes, the sun is over the equator, hence for the new and full moons that occur at these times, when both the sun and moon are nearly vertically over the equator and their two prominences are almost exactly one on the other, unusually high tides happen and such are known as the 'equinoctial spring tides.'

Various Causes which affect Tides.—At the time of eclipses, when the sun and moon are in a line, unusually high tides will occur, and it is easy to understand that when the moon is in 'perigee,' that is, nearest to the earth, its effect will be greater than when it is in 'apogee,' that is, as far away from the earth as it can be For a similar reason the tides in winter are higher than in summer because the earth is then nearer the sun.

The sun moves in a year from the tropic of Cancer, $23\frac{1}{2}°$ north of the equator, to the tropic of Capricorn, $23\frac{1}{2}°$ south of it, and back again. When the sun is over the tropic of Cancer, the tidal prominence raised by it has the greatest height in that latitude, in fact, the prominence moves with the sun north and south of the equator during the year. The change in the height of the tides due to the change in the sun's declination is not, however, considerable.

Establishment of a Port.—So far we have described the phenomena that would occur if the waters on the earth everywhere yielded immediately to the attractive force of the sun and moon. This, however, is not the case. Water, like everything else, requires time for a force to set it in motion. Hence, even if the earth were covered uniformly with water, high tides would not happen directly under the moon but some hours after it had passed the meridian; the moon would drag high tides after it at a certain angle, and the interval of time between the meridian passage of our satellite and high water would be the same all over the earth. But such considerations are entirely theoretical, and the phenomena would only occur if the tidal wave could flow everywhere without interruption. The actual phenomena of the tides are infinitely more complicated; the unequal depths of the ocean in various localities, the irregular conformation of the land, the varying widths and lengths of the channels, the action of the wind and many other causes make the interval between the moon's meridional passage and high tide different for different places on the earth. Indeed, this interval can never be theoretically determined, and must be found by observation. The time that elapses each day between the passage of the moon across the meridian and high water is called the 'luni-tidal interval.' These intervals vary slightly for reasons we have before indicated. The average of all the intervals in a semi-lunation, that is, the average interval between the time of high water and the preceding passage of the moon across the meridian, is called the average or 'mean establishment of a port.' The following is a list of some establishments:—

	hour	mins.		hour	mins.
Aberdeen ...	1	0	Southampton ...	10	30
London Bridge	1	58	Belfast	10	43
Land's End ...	4	30	Dover	11	12
Falmouth ...	4	57	Brighton ...	11	15
Swansea Bay ...	6	10	Liverpool ...	11	23
Bristol	7	13			

Since the 'tide interval' between any two places is always nearly the same, if the time of high water in any port be known on any day that at any established port may be calculated. Thus, the establishments of the ports of London and Bristol differ by 5 hrs. 15 mins. The times of high water at London Bridge on March 5th are 6.9 a.m. and 6.33 p.m. Hence, the corresponding times for Bristol are 6.9 + 5.15 and 6.33 + 5.15, that is, 11.24 and 11.48 respectively.

Tidal Range and Tidal Motion.—The difference of level between high and low water is called the 'range of the tide.' This range is different for different places, and is chiefly dependent upon the shape of the land, though many other causes operate. Before giving examples of these, it may be well to point out that there is no actual transfer of water by the tidal wave like there is in a river. The effect of the tidal action of the sun and moon is merely to cause the particles of water to rise and fall, and not to give them a motion of translation. It is well known that if one end of a rope be shaken a wave passes along it, yet each part of the rope only moves up and down. The motion of the tidal wave is precisely similar. In shallow depths of water an accumulation of such motion occurs and produces 'tidal currents' like those on the English coast.

Large Ranges and Bores.—It is easy to understand that in deep estuaries or creeks opening like a funnel in the direction of the tidal wave, the range is very much greater than elsewhere, for as the width of the creek decreases the height of the tidal wave must increase and the greater must be its velocity. As examples of places so situated, that of Chepstow, in the Bristol Channel, may be quoted; there the difference between high and low water, or the tidal range, is from 60 to 70 feet. The range in the Bay of Fundy is about 100 feet; at St. Malo and Bristol it is 40 feet; the London Docks, about 22 feet; Liverpool, about 15 feet; and Portsmouth and Plymouth, 12 feet.

In estuaries that are wide at the mouth and contract like a funnel the converging tidal wave rushes up the river like a wall of water. Such great waves are called *bores*. Some rivers remarkable for their tide-bores are the Severn, Seine, Amazon, and the Hoogly branch of the Ganges, where the bore travels 70 miles in four hours at a height of about seven feet. The bore of the Tsien-Tang in China is said to have a front about 30 feet high, to be four or five miles across, and to advance at the rate of about 25 miles an hour.

Tides in Rivers.—A tidal river is usually defined as one visibly affected by the ebb and flow of the tide. But it always happens that the variation between the heights of high and low water becomes indistinguishable at a certain distance from the river mouth. This distance is, to a large extent, determined by the depth of the river and the velocity of the flow. The following table shows the relation of range to distance in the case of the Thames :—

	Range.	Distance from Mouth of Thames.
London Bridge ...	18 ft. 10 in.	... 60 miles.
Putney	10 „ 2 „	... 67 „
Kew	7 „ 1 „	... 73 „
Richmond	3 „ 10 „	... 76 „
Teddington ...	1 „ 4 „	... 79 „

Small Ranges.—Where promontories or headlands jut out into the sea the tidal range is frequently small; thus at Wicklow it is only 4 feet, at Weymouth 7 feet, and at the Needles 9 feet.

In very large open tracks of water like the Pacific and Atlantic Oceans the range rarely exceeds 5 or 6 feet, and in narrow enclosed seas like the Baltic and Mediterranean, the tidal range is very small; indeed these seas are practically tideless. At Toulon the range is only about a foot, at Porto Rico (St. Juan) and in the Mediterranean about 18 inches, and St. Helena 3 feet.

Since the force producing tides acts everywhere, the height of water in lakes and land-locked seas should be somewhat affected. In the Caspian Sea and in Lake Superior the variation in level is imperceptible; but a tide of about $1\frac{3}{4}$ inches has been detected in Lake Michigan, and one of about $\frac{3}{4}$ of an inch in Lake Erie.

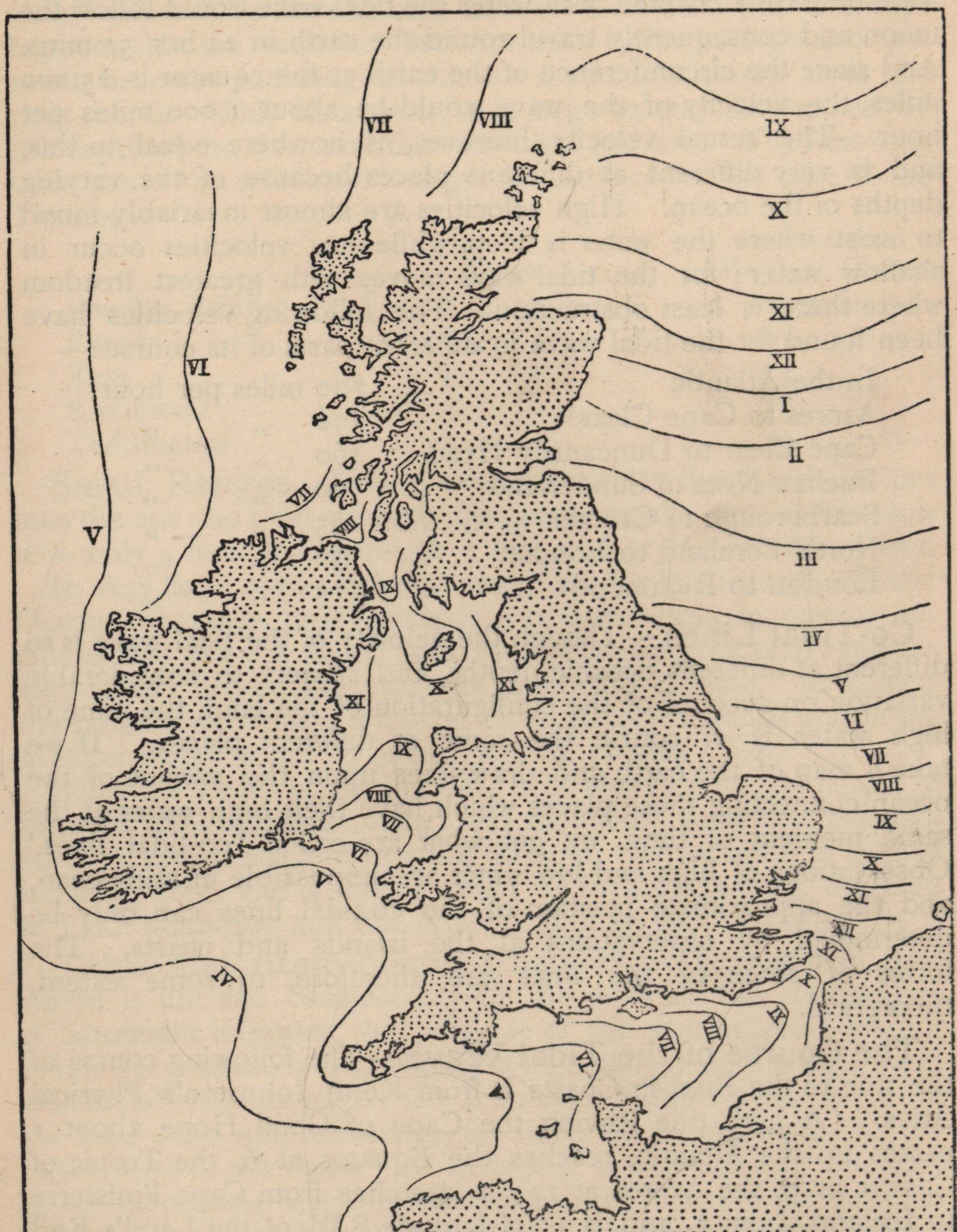
Tides and Atmospheric Changes.—The height of tidal waves is affected considerably by the state of the atmosphere. A barometer indicates the pressure of the atmosphere—when it is low the pressure is low, when it is high, the pressure is high—and it is found that the higher the barometer the less is the height of the tidal wave, and conversely, the lower the barometer the higher is the level of the water. At Liverpool a depression of one inch in the barometric height means a rise of 10 inches in the elevation of the Mersey high water mark, and at the London Docks a difference of one inch in barometric height means a difference of about 7 inches in the height of the tide. Tides in rivers are also considerably affected by winds, and heavy rains often mask them altogether.

Velocity of the Tidal Wave.—If the surface of the earth were uniformly covered with water the tidal wave would follow the moon and consequently travel round the earth in 24 hrs. 51 mins. And since the circumference of the earth at the equator is 25,000 miles, the velocity of the wave would be about 1,000 miles per hour. The actual velocity, however, is nowhere equal to this, and is very different at different places because of the varying depths of the ocean. High velocities are almost invariably found to exist where the water is deep, while low velocities occur in shallow water; for the tidal wave moves with greatest freedom where there is least obstruction. The following velocities have been found for the tidal wave in different parts of its course:—

In the Atlantic	700	miles per	hour.
Azores to Cape Clear	500	,,	,,
Cape Clear to Duncansby Head	160	,,	,,
Buchan Ness to Sunderland ...	60	,,	,,
Scarborough to Cromer	35	,,	,,
North Foreland to London ...	30	,,	,,
London to Richmond	13	,,	,,

Co-Tidal Lines.—Though the velocity of the tidal wave is so different at different oceanic depths, and subject to considerable variation on account of the configuration of the land, the time of high water is of course the same at different places. If we take a map of the earth and draw lines upon the surface of the ocean connecting those places which have their high water at the same moment of time, we get what are called 'co-tidal lines.' Observations of high and low water are impossible in mid-ocean, and the approximate position of the co-tidal lines can only be determined by observations at the islands and coasts. The forms of some of the lines are therefore, to some extent, theoretical.

The Course of the Tidal Wave.—The following course of the tide to the English Coasts is from Keith Johnston's Physical Atlas. 'A high tide leaving the Cape of Good Hope about 1 passes up the Atlantic, reaches the Equator at 6, the Tropic of Cancer at 9, the Azores at 12; it stretches from Cape Finisterre to Iceland about 3, and is 1° of latitude S.W. of the Land's End about 4. The Northern portion sweeps round the Isle of Lewis at 7 and the Orkneys at 8, at 11 it reaches Peterhead and Eagersund in Norway, at 12.30 Aberdeen and the Naze, at 2 Edinburgh, at 4 Flambro' Head, at 7 Boston, and at 8.30 Great Yarmouth.


VII
VIII
IX
X
XI
XII
I
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VI

A second portion passes up St. George's Channel, reaching St. David's Head at 6, the Isle of Man at 10, Belfast and Port Patrick at 11. The Southern portion passes up the English Channel, reaching Falmouth and Morlaix at 5, Portland Bill and Cape la Hague at 7, the Isle of Wight and Harfleur at 8, Deal and Calais at 11, Ramsgate and Dunkirk at 12, London Bridge at 2.15, Yarmouth at 3, and the Coast of Jutland at 1.'

The co-tidal lines round the British Isles are fairly well determined. Their general arrangement is shown in Fig. 68.

Changes in the Obliquity of the Ecliptic.—The angle between the plane of the equator and the plane of the ecliptic appears to have undergone a gradual diminution in historic time. This will be seen from the following comparison :

Date.	Name of Observer.	Obliquity.
200 B.C.	Eratosthenes	23° 51′ 15″
1437 A.D.	Ulugh Beigh	23 31 58
1690 A.D.	Flamsteed	23 28 48
Present time	... ...	23 27 8

The rate of diminution is about 46″ in 100 years, and it may be thought that in the course of ages the two planes will coincide. According to gravitational theory, however, the total variation cannot exceed 1° 20′, and this must take 10,000 years for its completion.

Effects of Change of Obliquity.—The latitudes of stars are counted from the plane of the ecliptic. If, then, the plane of reference has its position changed the chief effect produced will be a change of stellar latitudes. This is borne out by observation. The latitudes of stars south of the ecliptic are slowly, very slowly, diminishing, while those north of the ecliptic are as gradually increasing. Another effect is to give the line of equinoxes a direct movement of about 0″·18 a year along the celestial equator. This causes a slight decrease of right ascensions and longitudes, for both these co-ordinates are reckoned from one of the points where the equinoctial line pierces the sky. And since the sun moves in the ecliptic its meridian altitude must vary, and also its amplitude of rising and setting on any day in the year.

Cause of Changes of Obliquity.—The displacement of the ecliptic plane is produced by the action of the planets on the earth's orbit, the tendency being to bring the orbits of all the planets down to a common level. This secular variation is,

therefore, generally termed *planetary* precession, in contradistinction to *luni-solar* precession produced by the attraction of the sun and moon upon the equatorial protuberance of the earth.

Precession of the Equinoxes.—The longitudes of stars are counted along the ecliptic from the position of the vernal equinox, the right ascensions are counted along the equator from the same point. If the line of equinoxes had an invariable direction in space, the longitudes and right ascensions of stars would remain the same. A comparison of observations made at widely separated intervals of time shows a considerable increase in stellar longitude, so the vernal equinox must have moved backwards, and this movement is known as the 'precession of the equinoxes.' Luni-solar precession is produced by the action of the sun and moon, and tends to move the line of equinoxes backwards, that is, in the opposite direction to the earth's motion, at the rate of $50''.38$ a year. Planetary precession tends to move the line forwards by a small amount, and the general result is that the retrogradation is at the rate of about $50''.2$ a year.

Effects of the Precession of the Equinoxes.—The disturbing action of the sun, moon, and planets upon the earth produces the following effects:—

(1.) The line of equinoxes has a retrograde movement which takes it completely round the ecliptic sphere in 25,800 years.

(2.) The signs of the zodiac no longer coincide with zodiacal constellations. At one time the sun entered Aries at the spring equinox, and Libra at the autumnal equinox, while Cancer and Capricorn corresponded to the summer and winter solstices. The spring equinox now occurs when the sun is in Pisces; the summer solstice, when in Gemini; autumn equinox, when in Virgo; and the winter solstice, in Sagittarius.

(3.) The declinations of stars, being reckoned from the celestial equator, are changed, the greatest variation being twice the obliquity of the ecliptic, that is, about 47°. These changes are accompanied by changes in the amplitudes of the risings and settings of stars.

(4.) The extremities of the earth's axis, and therefore the celestial poles above them, describe circles round the poles of the ecliptic, the radius of each circle being equal

to the obliquity of the ecliptic, and the time taken to complete a revolution being 25,800 years. In consequence of this, the stars near the celestial poles vary from century to century.

(5.) The right ascensions and longitudes are increased, for they are reckoned from the retrograding vernal equinox.

(6.) The tropical year is shorter than the sidereal year (for the sun moves eastward, while the equinoxes are moving westward), and the difference between the two years is equivalent to the time the sun requires to pass over $50''{\cdot}2$, that is, about twenty minutes.

Nutation.—The precession of the equinoxes varies in amount from day to day. Instead of the direction of the earth's axis describing a proper circle round the poles of the ecliptic, it describes a wavy line. This small oscillation of the earth's axis, known as nutation, is caused principally by the moon's action. On account of it:—

(1.) Each pole of the earth (and therefore the celestial pole above it) describes the circumference of an ellipse having a major axis $18\frac{1}{2}''$ in length in 18·6 years, while the centre of the ellipse steadily travels in a retrograde fashion round the pole of the ecliptic in 25,800 years.

(2.) The declinations of bodies change slightly in a period of 18·6 years, and their longitude and right ascensions alternately increase and decrease in the same time. But nutation does not affect the position of the ecliptic plane, and therefore does not cause the latitudes of stars to vary.

Physical Cause of Precession.—Newton proved that the physical cause of the precession of the equinoxes arises from the spheroidal form of the earth. A sphere having the semi-polar diameter of the earth for a radius is less than the terrestrial spheroid by a shell of matter which can be supposed to be accumulated round the equator, where its thickness is about 13 miles. Luni-solar precession results from the differential attractions of the sun and moon upon this redundant mass. Consider first the attraction stress between the sun and the equatorial protuberance at the times of the solstices. (Fig. 69.) Both the portion of the protuberance nearest the sun and that on the farther side of the earth, are pulled towards the sun, but the pull is greater for the former than for the latter. This force of attraction can be resolved

into two, one parallel to the equator, the other at right angles to it. The tendency of the latter force is to diminish the angle which the plane of the equator makes with the plane of the ecliptic, and if the earth were not in rotation, the two planes would soon be made to coincide. But the inclination of these planes (the obliquity of the ecliptic) is practically constant, and the effect produced by the action in question is a gradual shift in the position of

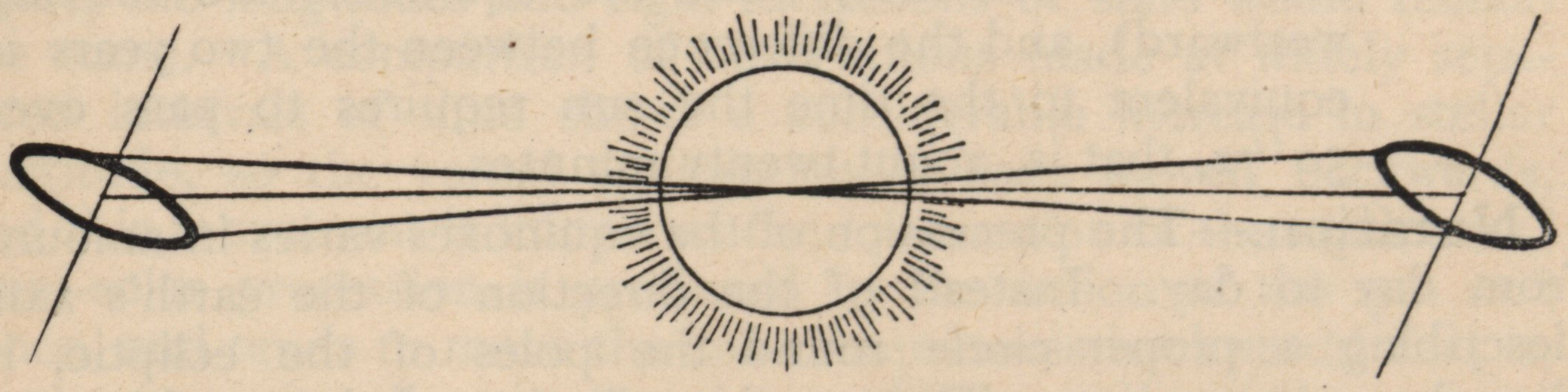


Fig. 69. The Earth's equatorial protuberance at the Solstices, showing the tendency of the Sun to pull it into the plane of the ecliptic.

the plane of the equator. When the earth is at the equinoxes the sun has no action tending to produce precession, for an equatorial diameter of the earth then lies in the ecliptic plane. The effects of precessional action are therefore constantly varying throughout the year. Twice a year, at the solstices, the effect of the sun is at a maximum; twice a year it is nothing, and on no two days in the year is it exactly the same.

Illustrations of Precession.—Sir. Robert Ball illustrates precession by means of a spinning top. When the top is rotating, as shown in Fig. 70, its axis slowly moves round the perpendicular to the point on which the peg rests. And for this reason: the top is pulled downwards by gravity, and if it had not a spinning motion it would fall. The result of the gravitational stress and the rotation is to cause the top to change its position, but not to change its inclination to the ground. As the spin decreases, however, the top sinks lower and lower, and finally settles down upon the ground. The action and

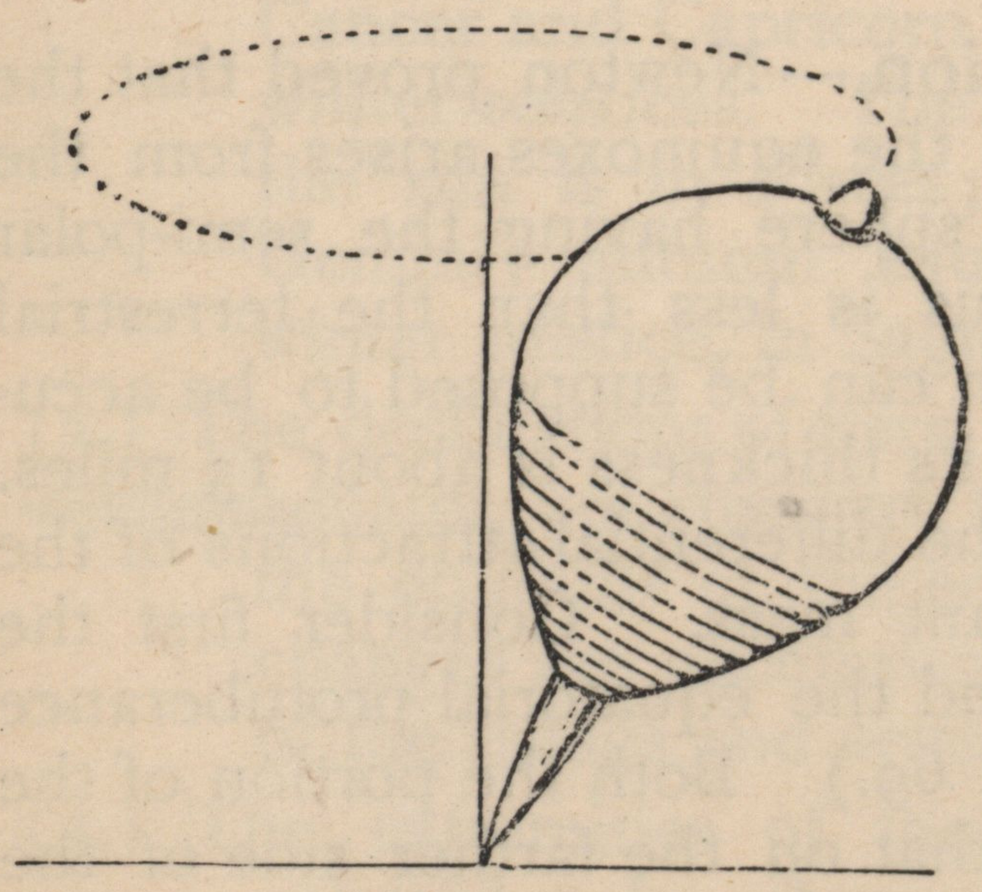


Fig. 70. Illustrating the precession of the earth's axis. (After Ball.)

the result are very similar when the sun and earth are considered. The top represents the earth, and the pull of gravity is analogous to the attraction of the sun, while the perpendicular indicates the axis of the ecliptic. The earth's axis moves round the ecliptic axis in precisely the same way that the axis of the top moves round a perpendicular to the ground.

Professor Lockyer represents the equatorial protuberance by a ring of soft iron in rapid rotation, and uses a magnet to attract the ring, in imitation of the attraction of the sun or moon. When the magnet is not near, the axis of the ring remains parallel to itself, but on bringing it into action, the parallelism is disturbed, and a slow movement of rotation occurs.

The Cause of Nutation.—It was shown in the section dealing with tides that the differential action of the moon upon the earth is greater than that of the sun. The moon's action in shifting the direction of the earth's axis should therefore be greater than the sun's, and this is really the case. Let QQ′ (Fig. 71) represent the earth's equator and MM′ the plane in which the moon revolves round the earth at the present time. In

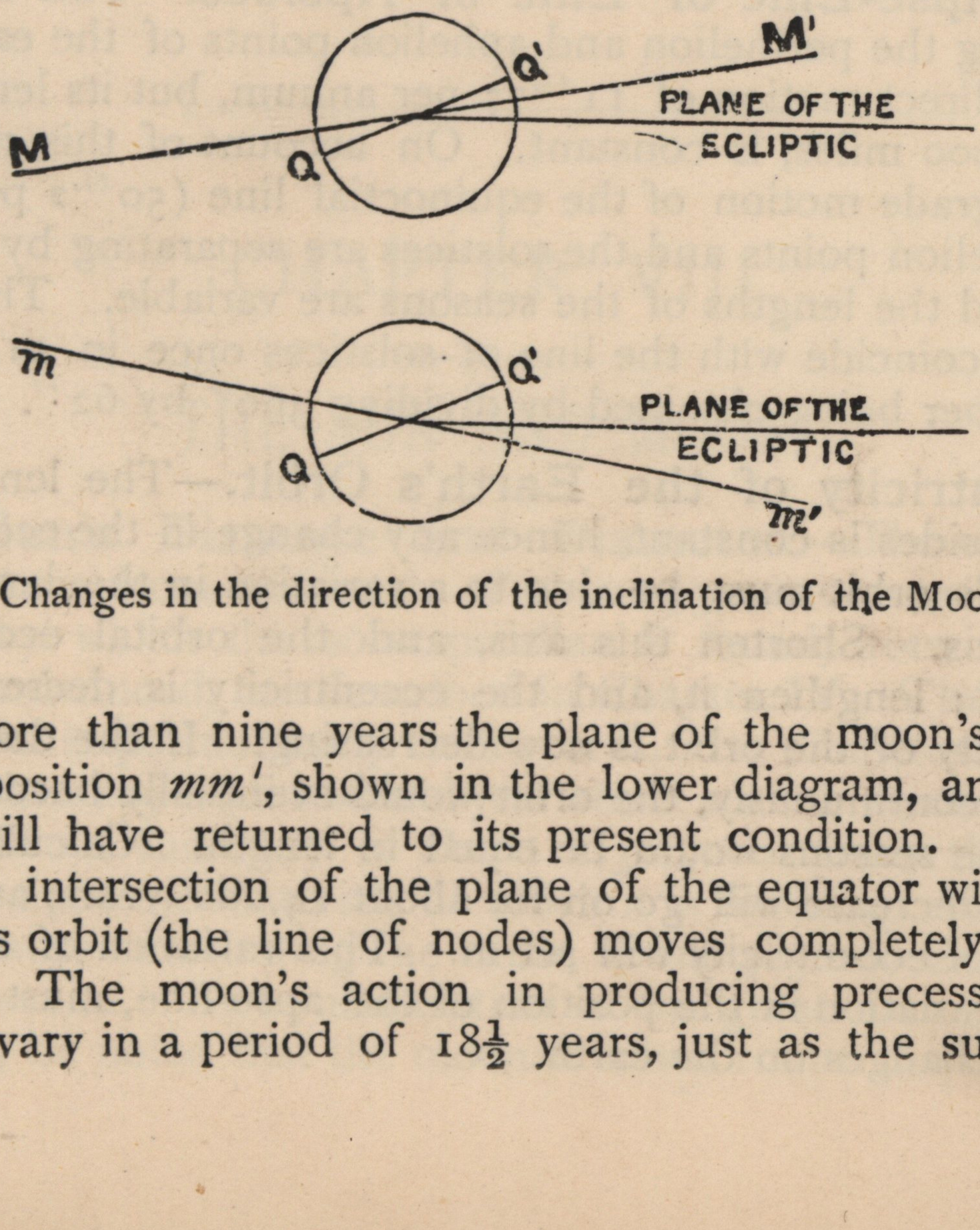


Fig. 71. Changes in the direction of the inclination of the Moon's Orbit.

a little more than nine years the plane of the moon's orbit will have the position *mm′*, shown in the lower diagram, and in 18½ years it will have returned to its present condition. In other words, the intersection of the plane of the equator with that of the moon's orbit (the line of nodes) moves completely round in 19 years. The moon's action in producing precession must, therefore, vary in a period of 18½ years, just as the sun's action

varies throughout the year. When the two planes coincide, lunar effect is nothing; it is greatest when the planes are inclined in opposite directions, and smaller when the direction of inclination is the same. Before the theory of nutation had been worked out, Bradley observed that the declinations of stars slowly increased for a period of nine years and then decreased, the greatest change amounting to 18″. In consequence of the combination of the effects of the sun and moon, the true path of the celestial poles round the poles of the ecliptic is in the form of a wavy curve. The moon's action sometimes increases the mean distance between the celestial and ecliptic poles and sometimes decreases it, while the mean motion is alternately quickened and retarded. And the result is that in 19 years (more accurately, 18 years 219 days) the pole of the equator describes an ellipse about its mean place, the major axis of which is 18″·5 and the minor axis 13″·7. The number of waves in the circumference of the path described by the celestial pole is $\frac{25800}{19} = 1,358$. And, since solar precession is not uniform, each wave must be made up of smaller undulations corresponding to the variation. This nutation is, however, too small to be observed.

The Apse-Line or Line of Apsides.—This is the line connecting the perihelion and aphelion points of the earth's orbit. It has a direct motion of 11″·77 per annum, but its length, about 184,000,000 miles, is constant. On account of this motion and the retrograde motion of the equinoctial line (50″·2 per annum), the perihelion points and the solstices are separating by about 62″ yearly and the lengths of the seasons are variable. The apse-line will only coincide with the line of solstices once in 21,000 years, this number being obtained by dividing 360° by 62″.

Eccentricity of the Earth's Orbit.—The length of the line of apsides is constant, hence any change in the eccentricity of the earth's orbit must be due to a variation in the length of the minor axis. Shorten this axis, and the orbital eccentricity is increased; lengthen it, and the eccentricity is decreased. The eccentricity of the orbit is now decreasing. If the decrease were to go on continuously, the orbit would eventually become circular and all the seasons would be equal in length. Calculation shows that the decrease will go on for about 24,000 years, and then an increase of eccentricity will set in. This variation of eccentricity, like the variation in the position of the apse-line, must cause great climatic changes on the earth.

QUESTIONS ON CHAPTER VII.

1. What are the causes and what are the effects of the precession of the equinoxes? (May, 1886.)

2. The sun's attraction at the earth's surface is much greater than that of the moon, yet the moon is the more important agent in producing tides. State the exact reason of this. (May, 1889.)

3. Explain why the influence of the moon is greater than that of the sun in causing tides. (May, 1888.)

4. Why is the influence of the moon on the tides greater than that of the sun? (May, 1887.)

5. How are the tides caused, and what is meant by 'Spring' and 'Neap' tides? (May, 1885.)

6. What is meant by the precession of the equinoxes? (May, 1883.)

7. State what you know about nutation. (May, 1878.)

8. Explain the precession of the equinoxes. (May, 1877.)

9. How is the precession of the equinoxes caused? (December, 1888.)

10. How are the apparent positions of stars changed by planetary and luni-solar precession respectively?

11. What variations do the seasons on the earth undergo in the course of ages, and what are the chief causes of the variations?

12. Define Apse-line, Line of Solstices, and Line of Equinoxes. Do these lines constantly point in the same direction? If not, what changes do they undergo?

CHAPTER VIII.

THE SUN AND MOON.

The Sun's Distance and Diameter.—The sun has a mean distance from the earth of about 93,000,000 miles. The methods by which the solar parallax is found, from which this distance is deduced, are described in Chapter IV. The sun is by far the most important body to the earth. Its diameter is 866,000 miles, so that 109 earths would just about stretch across it. The volume of our luminary is about 1,300,000 times that of the earth, but since the materials of which it is made up are only $\frac{1}{4}$ as heavy as those constituting the earth, about 325,000 earths would balance the sun. As an illustration of the great diameter of the sun, it may be noted that the moon revolves round the earth in an

orbit at a mean distance of about 240,000 miles, and if it were possible to place the earth at the sun's centre and the moon at its proper distance from the earth, our satellite would only reach half way to the sun's circumference (Fig. 72).

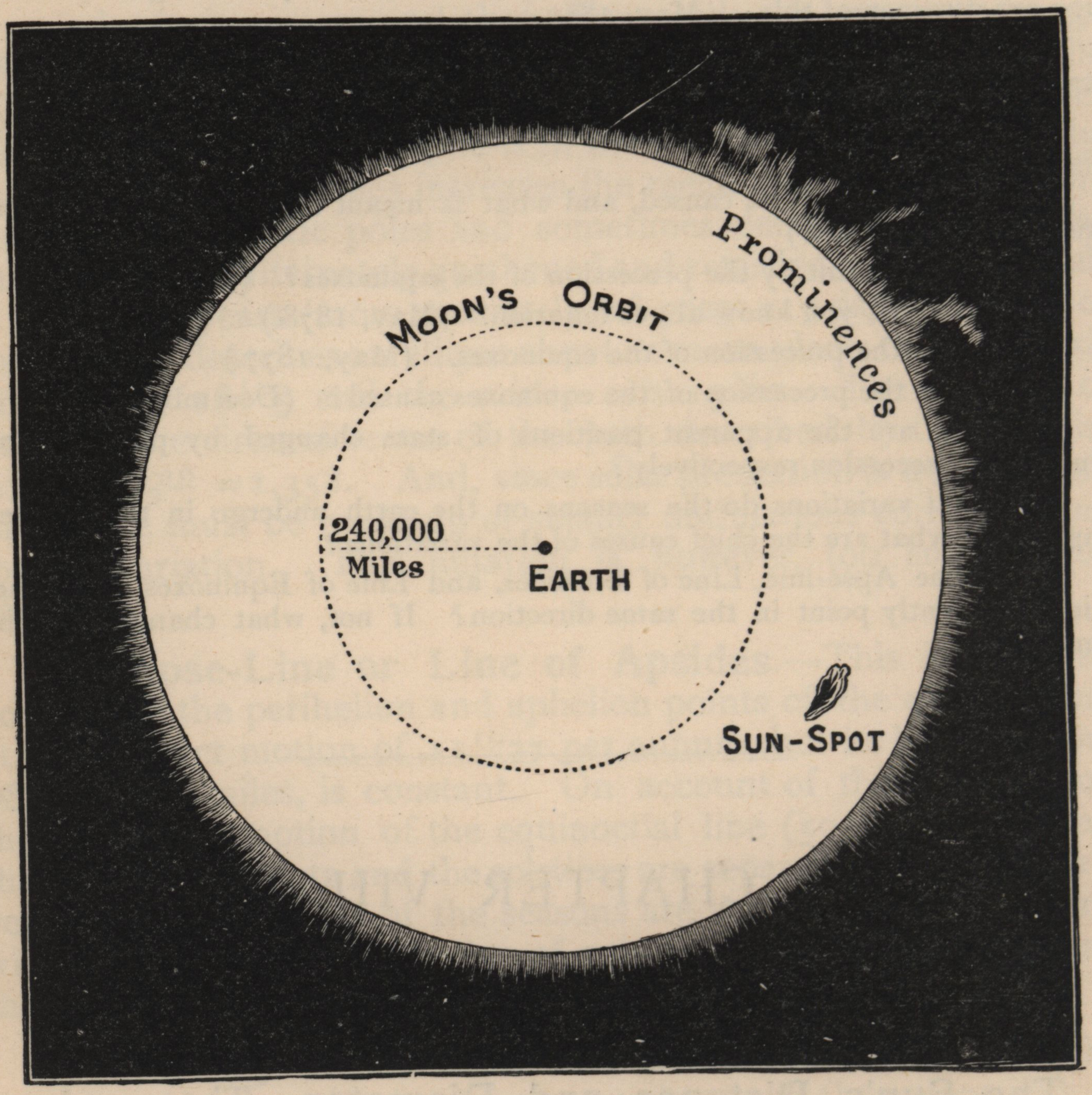


Fig. 72. Comparative dimensions of the Moon's Orbit and the Sun's Diameter.

How to Observe the Sun.—To investigate the true texture of the sun's visible surface, a telescope must be employed. But the precaution must be taken of covering the eye-lens of the instrument with a dark glass to cut off some of the sunlight, for if this were not done, the observer would probably lose his eye-sight. In general, the sun is not looked at directly. The light concentrated by the object glass of the telescope falls upon a slip

of plane glass fixed at an angle of 45° with the axis of the tube. Many of the rays pass through the glass; another part of the light is reflected from the first surface to an eye-piece fixed at right angles to the tube. (Fig. 73.) Though only a portion of the original beam is utilised, it is necessary to shield the eye by means of a dark glass over the eye lens. If it is desired to use an ordinary eye-piece on a telescope to observe the sun, the instrument should be directed towards our luminary and a piece of white card should be held at a short distance from the eye lens. An image of the sun will then be seen projected upon the card. Photography greatly assists astronomers in the study of the sun's surface. Every day throughout the year the sun is photographed. A permanent record is thus obtained which has the advantage of being absolutely accurate.

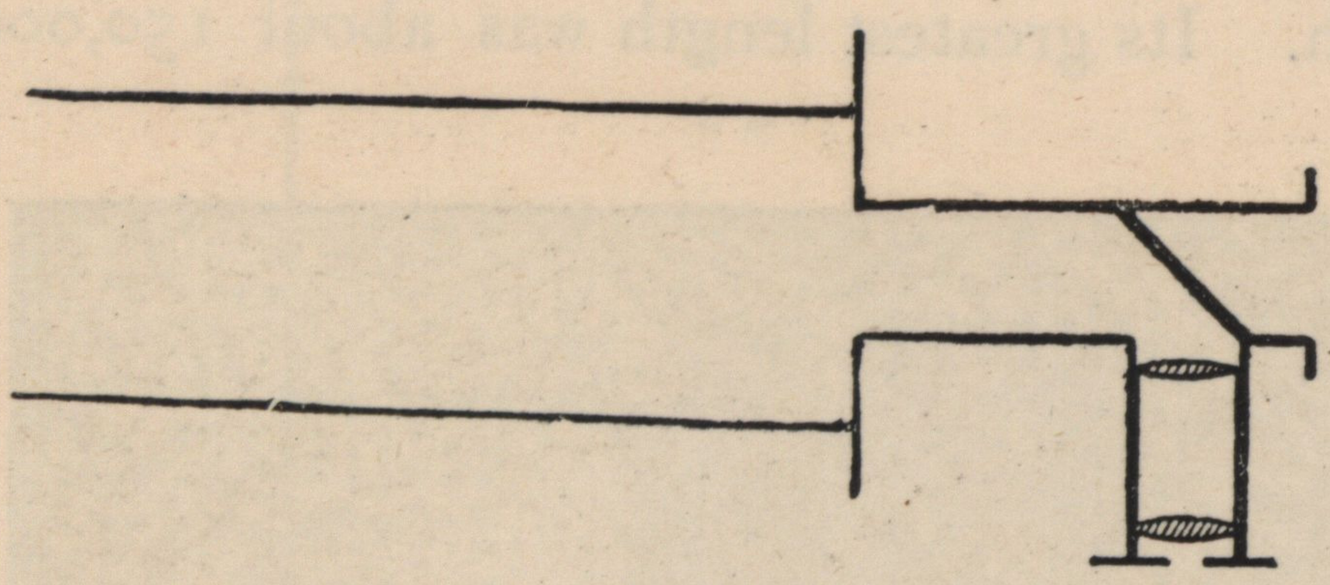


Fig. 73. Diagonal Eye-piece used for viewing the Sun.

The Photosphere.—The visible surface of the sun is termed the *photosphere*. To the unaided eye, it appears like a flat disc of uniform brightness, but when a telescope is used with a fairly high magnifying power, the photosphere is seen to have a mottled texture. Some parts are brighter than others, and the general effect has been compared to rice grains on a grey background. Indeed, the luminous masses are frequently called rice-grains, though some astronomers prefer to name them *nodules*. The smaller parts into which the rice-grains can often be broken up by means of a high magnifying power, are known as *granules*. There is very little doubt that rice-grains, or nodules, are clouds floating in the atmosphere of the sun similar to those which exist in the atmosphere of the earth, and that the granules are the tops of such clouds. (Fig. 74.)

Sun-Spots.—Dark spots are frequently seen upon the sun when viewed with a telescope, in fact, it is the exception rather than the rule for the sun's disc to be without these spots. They vary considerably in form and in size. Some appear like specks of dust and have an area of 400 or 500 miles; others are much

larger, and often a lot of spots occur grouped together. During February, 1892, one of the largest spot-groups ever observed appeared on the sun. At one time it occupied 2,850 millionths of the sun's visible disc, which corresponds to an area of 3,360,000,000 square miles, or about $\frac{1}{350}$ of the face of the sun turned towards the earth. Its greatest length was about 150,000

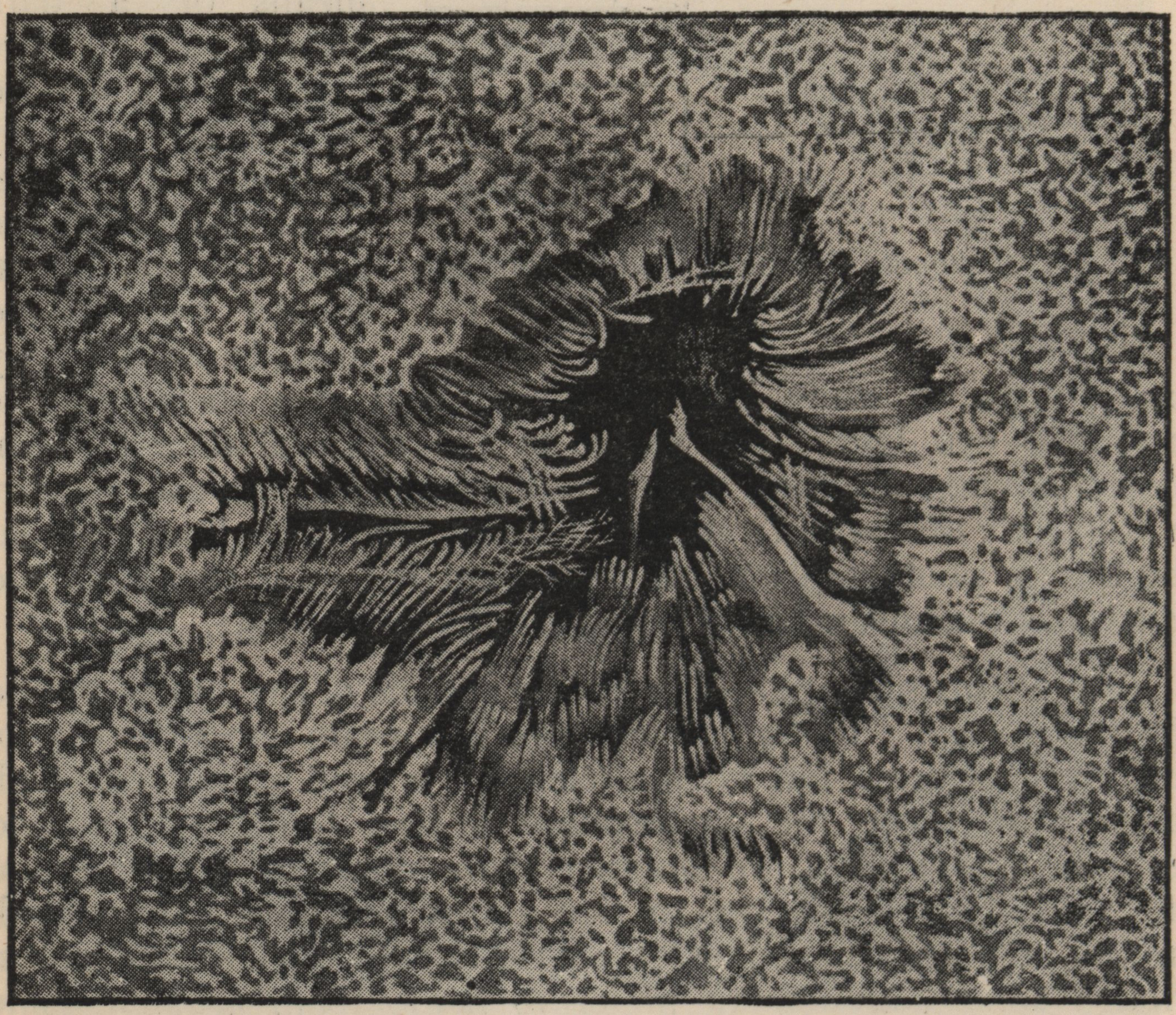


Fig. 74. Detailed structure of a Sun-Spot and the surrounding photosphere.

(*From a Drawing by Professor S. P. Langley.*)

miles, and the greatest width was, roughly speaking, half this amount. Thus it would take nearly nineteen bodies of the diameter of the earth to span the length of the spot, about nine to reach across it, and about seventy to fill the gap. This spot-group, and a few before it, was so large that it could be seen with the naked eye. A normal spot consists of a dark central portion termed the *umbra*, and a portion of a lighter shade, termed the

penumbra, fringing it. (Fig. 75.) A small portion still darker than the umbra can sometimes be distinguished near the centre. This is known as the *nucleus* of the spot. Occasionally spots

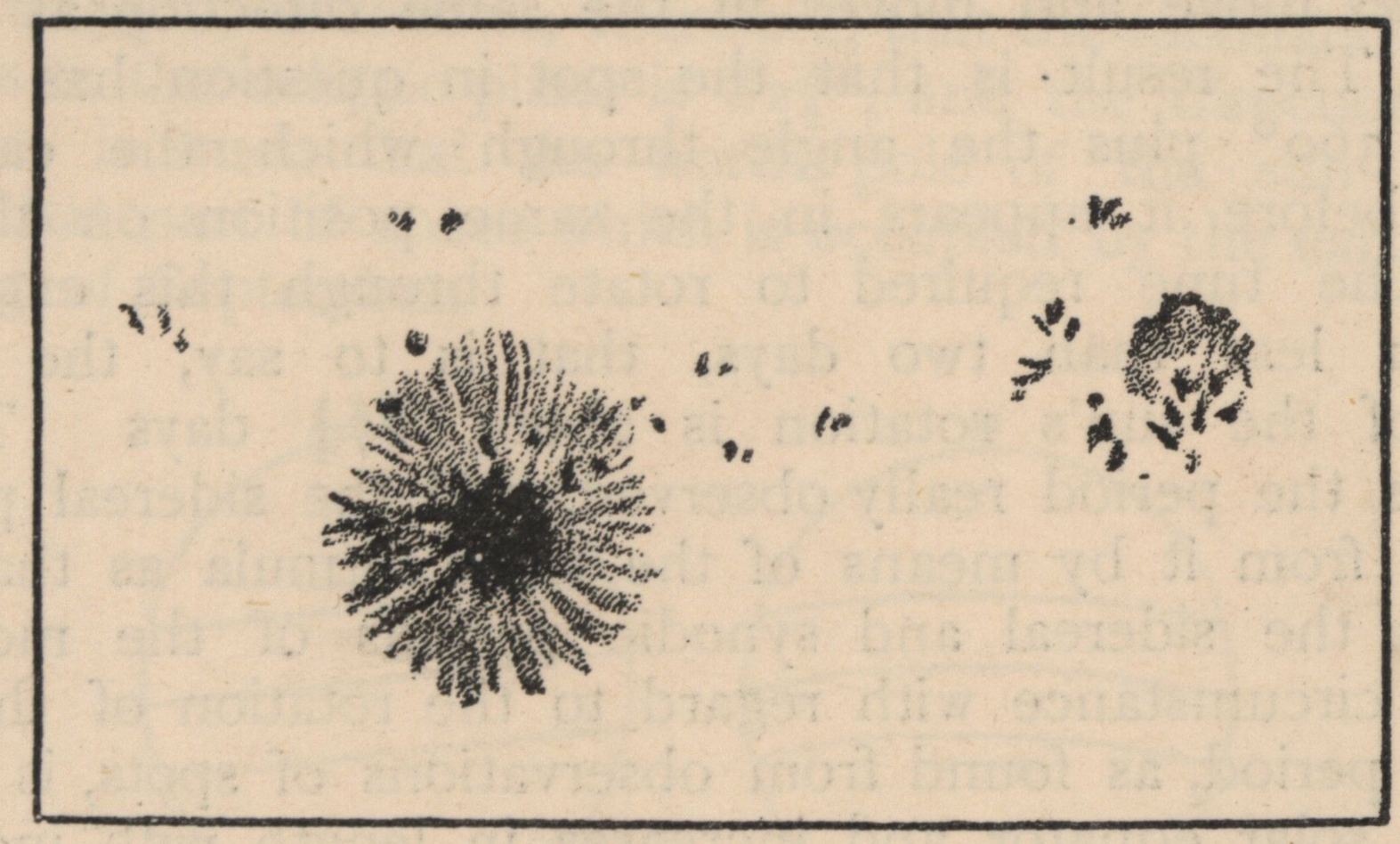


Fig. 75. Showing an ordinary Sun-spot and a number of small spots seen on the sun, June 20th, 1889. (*From a Drawing by Professor Ricco.*)

appear without a nucleus, and others without a penumbra. The penumbra of a spot consists of photospheric nodules drawn out into forms which have been compared to those of *willow-leaves*. The willow-leaves point more or less towards the nucleus in one direction, while their outer ends occurring at different distances from the nucleus appear somewhat like the ends of a straw-thatch. On this account the drawn-out streaks around a spot are often termed *thatch-straws*. Bridges of luminous matter sometimes stretch across a spot from one side to the other (Fig. 76), and on rare occasions luminous masses overlie the umbra.

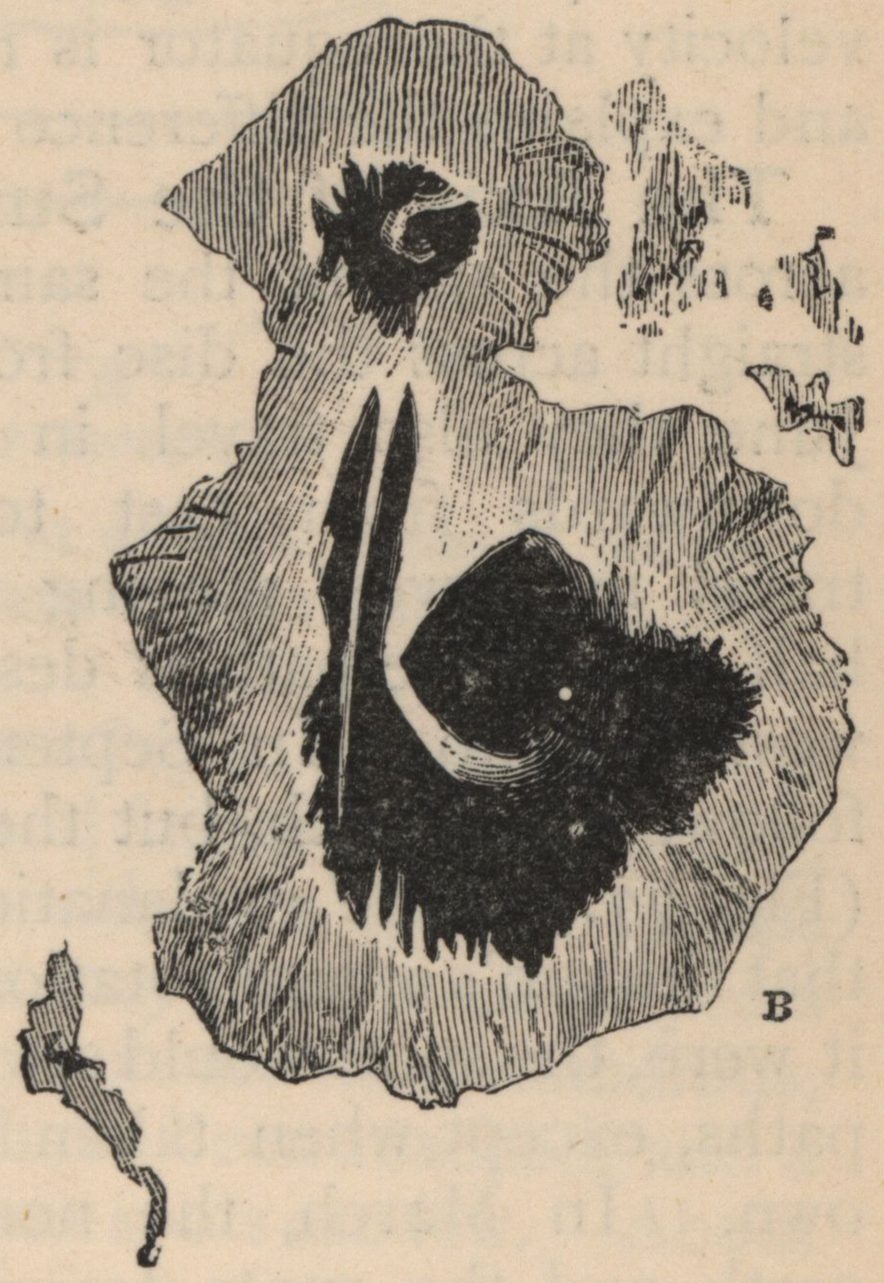


Fig. 76. View of a large Sun-spot, showing a luminous bridge extending over the umbra.

Rotation of the Sun.—By observing the sun from day to day, it is found that the spots move from east to west across the disc, which indicates that the sun is in rotation, like the earth. If the earth did not move round the sun,

the average time between two successive appearances of a spot in the same position on the sun's disc would be about $25\frac{1}{3}$ days. This is, therefore, the period of the sun's axial rotation. But the earth *does* move and moves in the same direction as the sun rotates. The result is that the spot in question has to move through 360° plus the angle through which the earth has moved, before it appears in the same position on the sun's disc. The time required to rotate through this extra angle is rather less than two days, that is to say, the synodic period of the sun's rotation is about $27\frac{1}{4}$ days This, of course, is the period really observed, and the sidereal period is deduced from it by means of the same formula as that which connects the sidereal and synodic periods of the moon. A peculiar circumstance with regard to the rotation of the sun is that the period, as found from observations of spots, is shortest near the solar equator, and increases in length with increase of solar latitude. A point on the equator performs a complete rotation in less than 25 days, in latitude 25°, the period is 26 days, and in latitude 50° it is nearly $27\frac{1}{2}$ days. Two possible explanations have been suggested to account for this variation. One is that the sun spots have a proper motion of their own, similar to that of cyclones on the earth ; the other asserts that the angular velocity at the equator is really greater than in higher latitudes, and explains the difference by reference to the nebular hypothesis.

The Axis of the Sun.—The spots do not constantly travel across the sun in the same paths. In December they travel straight across the disc from east to west in an uphill fashion, in June they also travel in a straight line, but the line slopes downwards from east to west. During March the spots travel in curves, moving upwards from the eastern limb until half the visible path is described, and then curving down to the western limb. In September the paths are similar to those followed in March, but the curves are in the opposite direction. (Fig. 77.) The explanation of these differences lies in the fact that the sun's axis of rotation is not perpendicular to the ecliptic. If it were, the spots would always appear to traverse the same straight paths, except when taken out of the course by motion of their own. In March, the north solar pole is tipped away from the earth and the spots describe upward curves; in September, this pole is turned towards the earth, and the spots apparently describe downward curves. In December and June, the line joining the centre of the earth to the centre of the sun is at right angles to

the sun's axis of rotation, consequently, the spots appear to travel in straight lines. Accurate observations show that the inclination of the plane of the ecliptic to the plane of the sun's equator is $7\frac{1}{4}°$. It follows, therefore, that the inclination of the sun's axis to the ecliptic plane is $82\frac{3}{4}°$, and the direction of this inclination is such that the north pole of the sun is tilted towards that part of space which is occupied by the earth at the beginning of September.

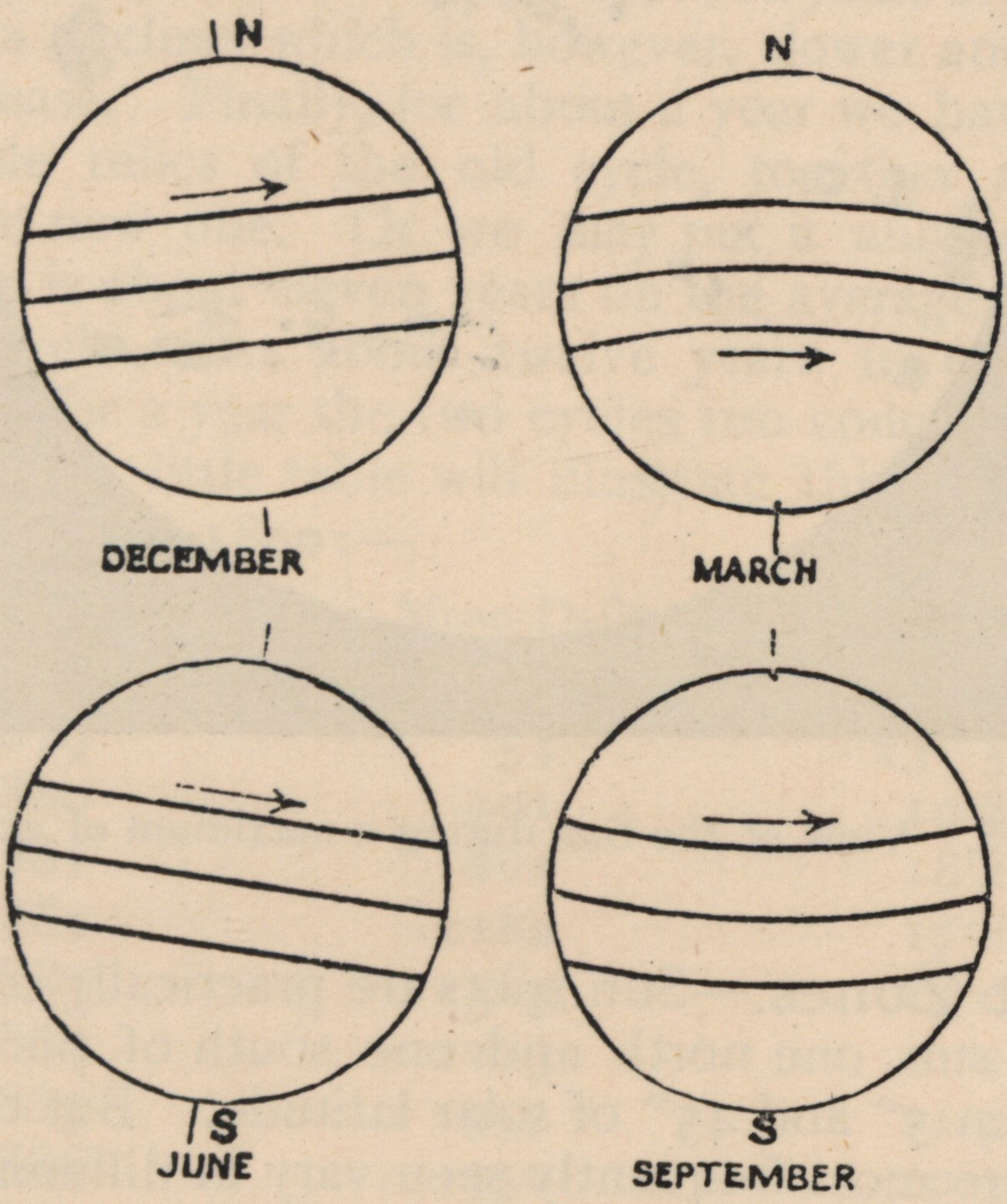


Fig. 77. The paths in which Sun-spots travel at different times of the year. The eastern edges are on the left and the western on the right of each disc.

Sun-spot Periods.—The proportion of spotted surface of the sun is at times much greater than others, and fluctuates periodically. During some years scarcely a day passes without a spot or groups of spots being seen, while several weeks may pass in other years without a spot being visible. When the spots are most numerous, a *maximum* of solar activity is said to have been reached, and a *minimum* of activity denotes the time when spots are few. About eleven years separate two consecutive maxima or two minima. A minimum was passed in July, 1889. Since then, spots have been more numerous than before. A maximum will be reached early in 1893, after which the activity will wane until 1900.

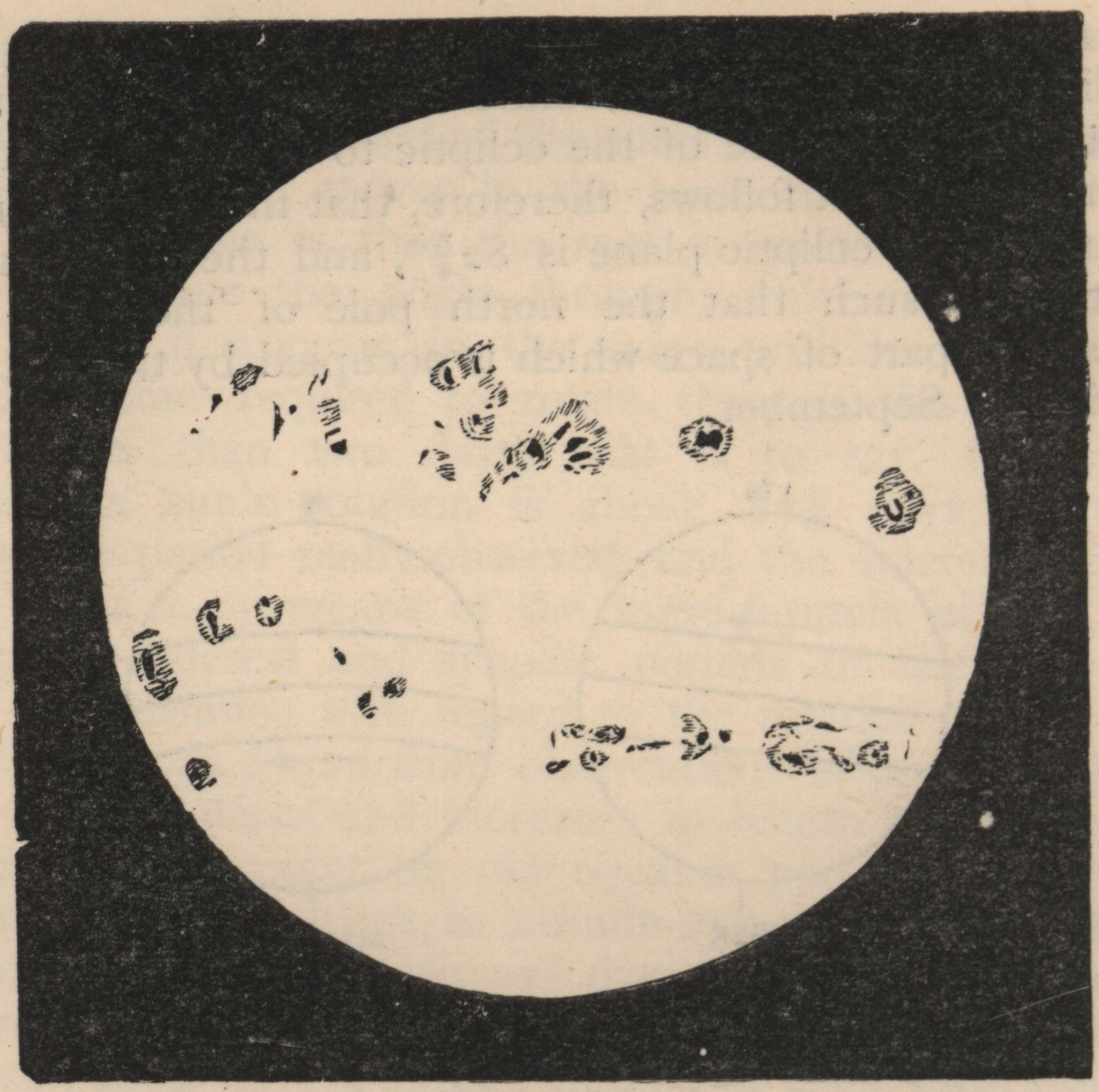


Fig. 78. View of the Sun during a maximum of activity.

Sun Spot Zones.—Sun spots are practically confined to two zones on the sun, one north and one south of the equator, contained between 5° and 45° of solar latitude. But the latitudes in which spots are most frequently seen vary in different parts of the sun-spot cycle. Mr. E. W. Maunder, of Greenwich Observatory, has described the series of changes which occurs, in *Knowledge*. In his words:—'We have three phases of the sun-spot cycle (1) Before minimum: spots few and diminishing; one spot zone, viz., that close to the equator. (2) After minimum: spots few, but increasing; three spot zones, viz., an equatorial zone and a zone of high latitude in either hemisphere, separated from the equatorial zone by a broad barren belt. (3) At or near maximum: spots numerous; two spot zones, one north and one south of the equator, the equatorial region itself being entirely barren. It follows, then, that the two barren belts of the second period are on the average the most prolific for the cycle as a whole, for they become the seats of spot activity just at the time when sun-spots are largest and most numerous.'

'There is, therefore, a steady and continuous tendency ever to seek lower and lower latitudes from the beginning of a cycle till its end. The first small and faint spots of the new cycle break out in the very highest latitudes attained. In this sense, the new period begins at once with its utmost vigour, and during the years in which it runs, its course is simply undergoing a continual decline. As to the numbers and areas of the spots the case is very different. For some three years there is a most marvellous and rapid increase, followed by two or three years of great activity. Then comes a decline, which is, however, slower and less striking than the increase. Finally, for about a year we have on the sun the last feeble relics of the old cycle, together with the first heralds of the new one. Or we may put it another way. The sun-spot cycle is about eleven years on the average, but each particular spot cycle takes about twelve years to entirely run its course, so that for a year the two cycles run concurrently.'

'The following little table will illustrate this for the last spot cycle, that of 1879—1890:—

Year.	Mean Daily Area.	Mean Distance from Equator of all Spots.
1879	54	23°·57
1880	491	19·80
1881	861	18·21
1882	1182	17·81
1883	1363	13·04
1884	1273	11·27
1885	957	11·76
1886	450	10·38
1887	211	8·44
1888	105	7·39
1889	61	6·34
1890	6	7·14

The mean area is expressed in millions of square miles, and for the years of overlapping, 1879, 1889, and 1890, only the spots proper to this cycle have been included.'

Sun Spots and Terrestrial Magnetism.—A delicately suspended declination needle is continually changing its direction. In the morning it swings slightly west of its mean position, reaching a maximum variation about two o'clock. It then swings back, and reaches the mean position about ten o'clock at night. The swing to and fro goes on day after day. 'This curious daily

motion varies in character and extent at different times. Notably, it varies with the season of the year, but for our present purpose its variation from year to year is most important. For it has been clearly established that, when we take average results for successive years, we find that this motion is greater in amplitude and force, in strict proportion, to the number and size of the spots upon the sun.' Though this is the case, it must not be concluded that sun-spots are the cause of magnetic variations. The general connection between the two phenomena has been placed beyond doubt, but the cause of the connection has not yet been explained. The Aurora Borealis also seems to be connected with sun-spots and fluctuations of terrestrial magnetism. In addition to these definite relations, it has been asserted that a connection exists between the sun-spot period and disturbances in our atmosphere and upon the earth; in fact, observations have shown that the amount of rainfall in India is subject to an eleven-year period of variation, and famines in India have been found to occur in years of drought coincident with periods of minimum sun-spots, whilst it has been said that trade is subject to similar periods of depression; but these connections have not been abundantly confirmed.

Sun Spots and Magnetic Storms.—Great disturbances upon the sun have on several occasicns been accompanied by disturbances of the earth's magnetic elements. The spot-group of February, 1892, is a case in point. On February 13, when the maximum area was reached, magnetic instruments were violently disturbed, and continued to be disturbed all through the day and evening until the following afternoon. The variation in magnetic declination was more than one degree, and the other elements were caused to vary through similar large amounts. The disturbance was greatest during the night of February 13, when an aurora borealis was seen at several places. There are two or three more similar coincidences, yet it cannot definitely be said that sun-spots and magnetic storms always run together. Large spots have appeared upon the sun without affecting the magnetic elements, and violent magnetic storms have occurred when very few and small spots have been visible.

Lord Kelvin has investigated the probability and possibility of the sun being an intensely strong magnet, with special reference to magnetic storms. Of a storm of this character, which was registered by the recording instruments in a number of magnetic observatories, he says :—' In this eight hours of a not very severe magnetic storm, as much work must have been done by the sun

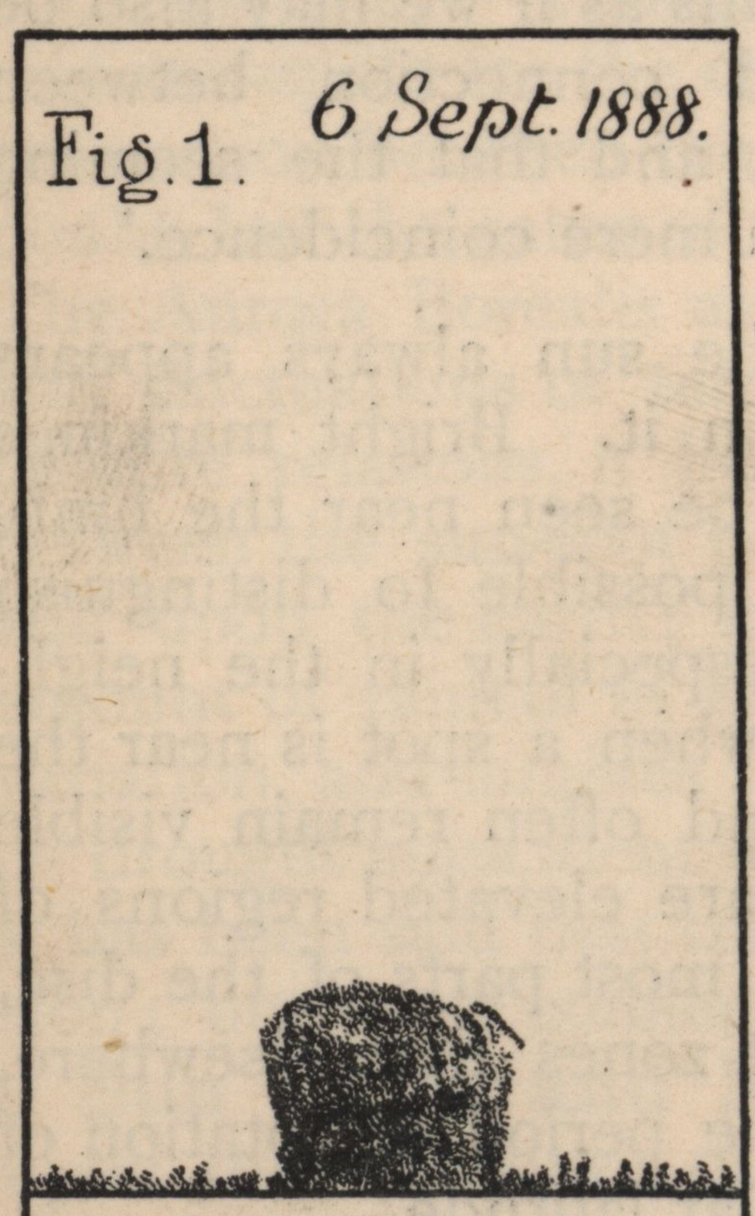
in sending magnetic waves out in all directions through space as he actually does in four months of his regular heat and light. This result, it seems to me, is absolutely conclusive against the supposition that terrestrial magnetic storms are due to magnetic action of the sun; or to any kind of dynamical action taking place within the sun, or in connection with hurricanes in his atmosphere, or anywhere near the sun outside. It seems as if we may also be forced to conclude that the supposed connection between magnetic storms and sun-spots is unreal, and that the seeming agreement between the periods has been a mere coincidence.'

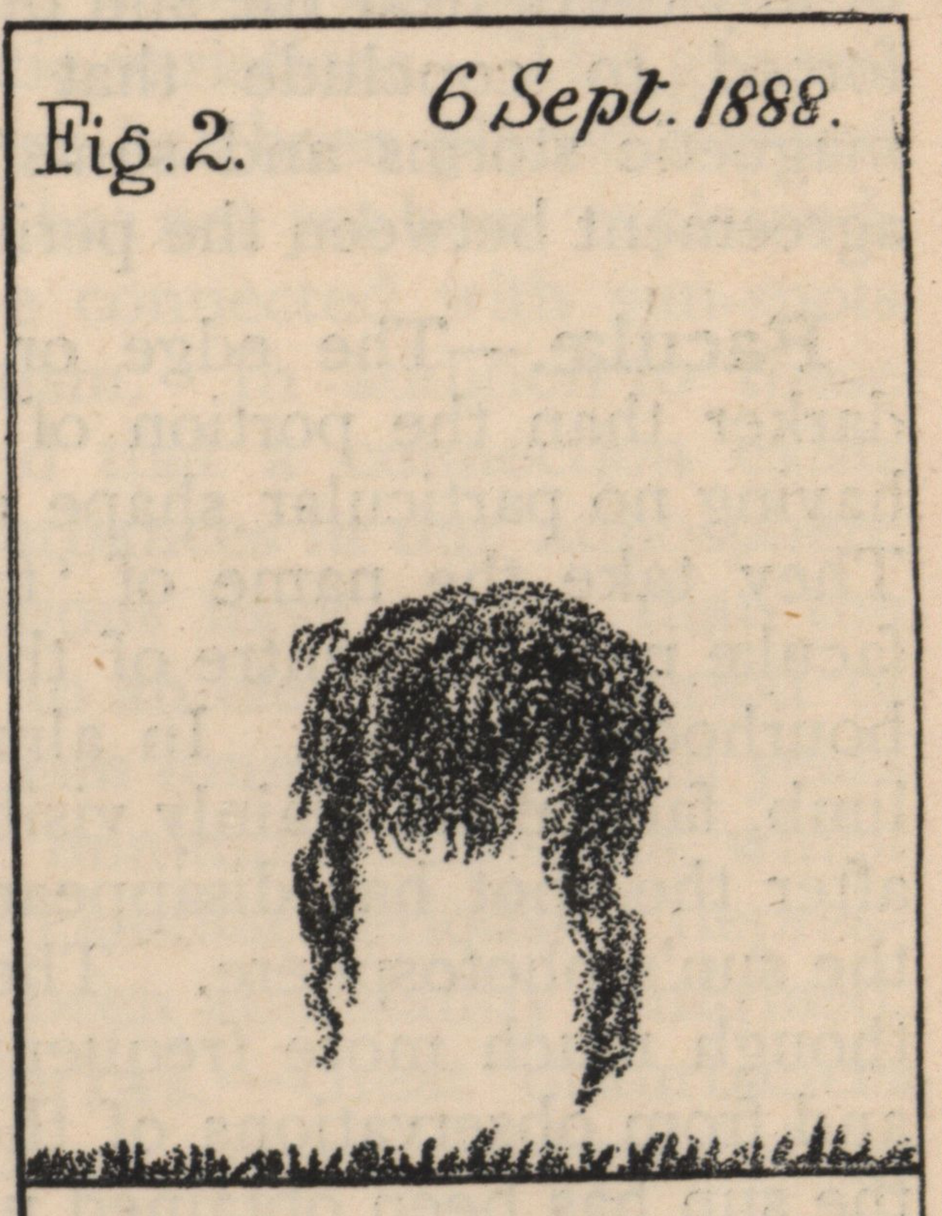
Faculæ.—The edge or 'limb' of the sun always appears darker than the portion of the disc within it. Bright markings having no particular shape can generally be seen near the limb. They take the name of 'faculæ.' It is possible to distinguish faculæ near the centre of the disc, more especially in the neighbourhood of spots. In almost all cases when a spot is near the limb, faculæ are plainly visible round it, and often remain visible after the spot has disappeared. Faculæ are elevated regions of the sun's photosphere. They are seen in most parts of the disc, though much more frequently in the spot zones than elsewhere, and from observations of their motions, the period of rotation of the sun has been obtained up to 75° of solar latitude.

Physics of the Photosphere.—The rice-grains of the photosphere are in all probability clouds which have been condensed out of the sun's atmosphere. They float in an atmosphere of gases and vapours like clouds of water-vapour float in our earth's atmosphere. The tops of these photospheric clouds are higher above the absorbing atmosphere than the lower parts, so they appear more luminous, and give a granulated appearance to the rice-grains. Sun-spots are undoubtedly cooler and lower than the surrounding photosphere. They have been proved to be cooler by direct observation; they are known to be cavities on account of the foreshortening effect seen as they cross the sun's disc. When we look straight down a spot, its penumbra appears more or less symmetrical, but as the spot is turned away from us, the penumbra is widened at the edge near the western limb, and narrowed at the edge directed towards the centre of the disc. What is more, spots have been photographed when just passing over the sun's limb and a slight notch has been found on the limb in the place of the umbra. Spots, then, are depressions; faculæ, on the other hand, are elevations of the photosphere. Sometimes faculæ are seen to

be elevated above the general level when passing over the sun's limb, but the fact that they are more luminous than the surrounding photosphere is in itself sufficient to show that they are above the general level.

Distribution of Solar Prominences.—The red flames or prominences seen around the sun during a total eclipse have







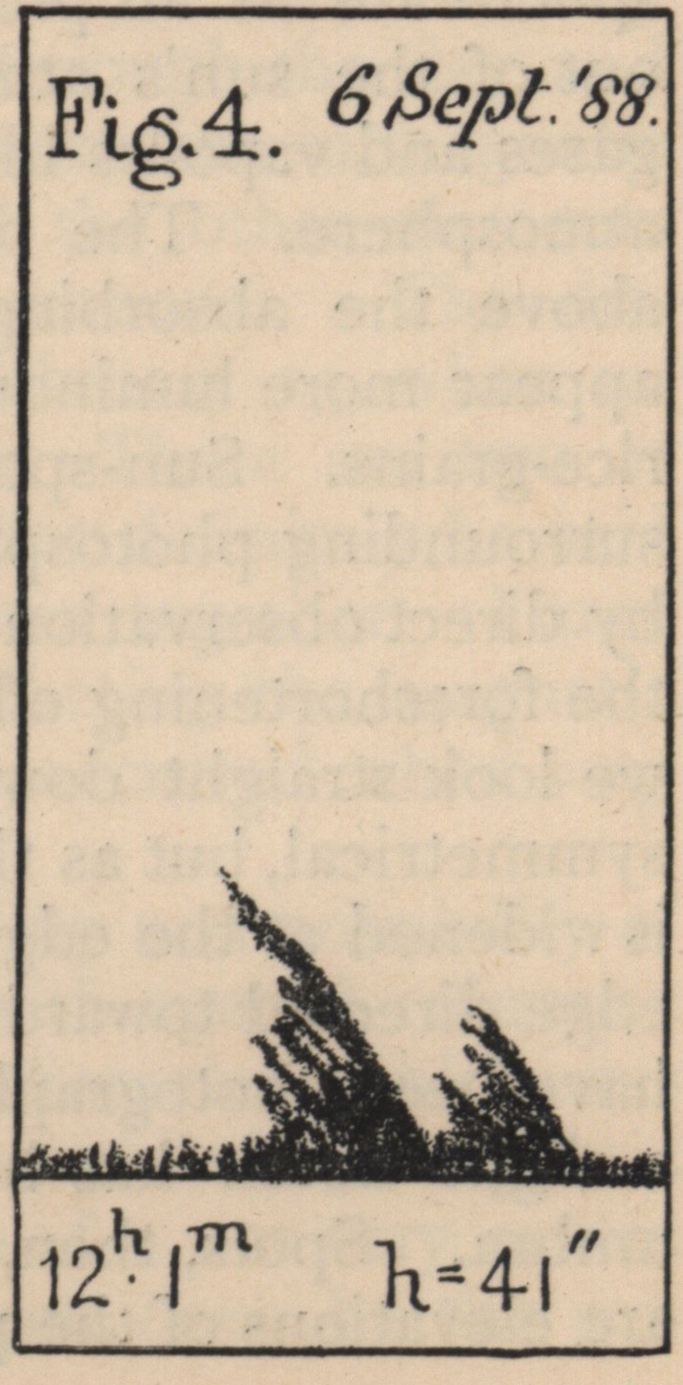


Fig. 79. A Solar Eruption, observed at Kalocsa, Hungary, by Jules Fenyi; *h* signifies the height above the sun's edge, expressed in seconds of arc, 1″ = 450 miles.

already been described. By means of the spectroscope, it is possible to see prominences at any time when the sun is shining, and in a few observatories a record is kept of the form, extent and distribution of the phenomenon. Some prominences are shot out from the sun, like material ejected by a volcanic eruption. These are termed *eruptive* prominences. (Fig. 79.) Others retain the same form for hours and days, and are known as *quiet* or *quiescent* prominences. Eruptive prominences are most frequently seen between the latitudes which limit the sun-spot zones. Quiet prominences, like spots without an umbra (veiled spots) and faculæ, are found all over the disc and in all latitudes.

Periodic Variation in the Latitude of Solar Prominences.—The mean latitude in which eruptive prominences occur varies periodically in the same way as that of spots. Observations show that about the time of maximum solar activity prominences occur nearest the sun's equator; the mean latitude for both hemispheres in the second year after the last maximum (1885) being 27°·5. There was then a rapid general increase in the latitude of most frequent occurrence up to the minimum epoch, the mean latitude for both hemispheres in the year following the last minimum—that is, in 1890—being 41°·3. In other words, up to the commencement of the minimum period prominences approach the equator. They then appear in high latitudes, to descend again to the equator in an eleven-year cycle. Upon consideration, this variation is what would be expected, for all solar phenomena must be connected, though the connection between them may not as yet have been firmly established.

The Sun's Light.—The only artificial light which approaches the light of the sun in intensity is the electric light. The lime-light, produced by letting an oxy-hydrogen flame play upon a ball of lime, is about $\frac{1}{150}$ as bright as the sun. Cover the sky with full moons and the light received would only be one-eighth that of the sun, for 600,000 full moons would be required to match the light of our luminary, and about 7,000,000,000 stars as bright as the brightest in the heavens.

The Sun's Heat at the Earth's Surface.—To measure the intensity of the sun's heat at the earth's surface, an instrument known as the *pyrheliometer* is used. By means of it a solar beam of known cross section falls upon a substance of known specific heat for a known time. The rise in temperature gives the amount of heat received in that time, and by making determinations with the sun at different altitudes, the amount absorbed by the earth's

atmosphere can be estimated. Pouillet's pyrheliometer is thus described by Deschanel:—'At the upper end, next the sun, is a shallow cylinder composed of very thin copper or silver, filled with water in which the bulb of a thermometer is inserted, the stem being partially enclosed in a hollow tube which supports the cylinder. At the lower end of the tube is a disc equal and parallel to the base of the cylinder. This is intended to receive the shadow of the cylinder, and thus assist the operator in pointing the instrument directly towards the sun. The cylinder is blackened in order that its absorbing power may be as great as possible.' To use the instrument, it is first turned towards the sky but screened from the sun's rays for, say four minutes. The temperature is then noted, and the instrument is pointed directly at the sun for the same time, thus receiving direct solar rays upon the blackened end of the cylinder. The rise of temperature is noted, and the instrument is again screened and turned towards the sky for four minutes. Half the sum of the two differences observed when the instrument is pointed towards the sky, gives the amount of heat lost during observation, and by adding this to the rise of temperature observed with the instrument pointed towards the sun, the rise of temperature due to the sun's rays is obtained. Knowing the thermal capacity of the instrument, the quantity of heat received in the four minutes of observation on a surface of known area can be calculated. The results obtained show that if the earth were stripped of its atmosphere 'the heat sent yearly by the sun to the earth would be sufficient to melt a layer of ice 30 metres (30·7 yards) thick spread over the surface of the earth.'

The Sun's Heat.—Knowing the radius of the sun, the intensity of solar radiation at the earth's surface, and the distance of the earth from the sun, we can calculate the intensity at the sun's surface by the law of inverse squares. From the result thus obtained it appears that at the photosphere of the sun the amount of heat sent out from a square yard in a second is something like 45,000 times greater than that received on a square yard of the earth. But the sun emits heat in all directions, and the earth only intercepts a few of the rays, in fact, the earth only occupies $\frac{1}{2200000000}$th of the surface of an imaginary sphere having a radius equal to the earth's distance from the sun, and all parts of this sphere are equally illuminated. Taking this fact into account it is found that a layer of ice one mile thick would be melted at the sun's surface in about $2\frac{1}{2}$ hours, and about 12 yards in one minute. This amount, however, is far from being accurately known, for

some writers state that 50 or 100 yards of ice per minute would be melted. The investigations of Pouillet and Herschel on the intensity of solar radiation led them to conclude that the mechanical value of the radiation of one square metre of solar surface is 78,000 horse-power. Langley found a value for the intensity 1·7 times higher than that obtained by the two above investigators. This gave the energy from a square metre of the sun's surface as 133,000 horse-power.

The Sun's Temperature.—Numerous attempts have been made to determine the sun's temperature, and the results obtained range from 1,500° to 5,000,000° on the centigrade scale. The difficulty of the determination arises from the fact that we are unable to say at what temperature the substances existing in the sun would have an intensity of radiation equal to that calculated for the sun's surface. Laboratory experiments show the radiating power up to a certain temperature, but for temperatures beyond this the rate has to be estimated, and the estimates may, of course, be far from the truth.

Sources of the Sun's Heat.—The sun has been radiating light and heat into space for millions of years. Its temperature was once much higher than it is now, though even now it is higher than that of any terrestrial heat source. If we calculate how much the temperature of the sun would be decreased annually by the radiation from his surface, we find it to be from 5 to 10 degrees. At this rate our luminary would cool right down to the temperature of the earth in a few thousand years. Two theories have been propounded to account for the heat that must be set up in the sun to keep its temperature so nearly constant. One is that the small bodies swarming in space, and called meteorites, clash against our luminary and increase the temperature by impact upon its surface. This, however, will only account for a small portion of the sun's heat, and the theory generally accepted is that the ball of luminous matter generates enough heat by its contraction to make up almost the entire loss. In fact, it has been calculated that the contraction which would reduce the sun's diameter $\frac{1}{10000}$ part would generate sufficient heat to last for 2000 years.

The Sun's Life.—With regard to the past and future of the sun, Lord Kelvin, whose authority is recognised in physical science, has shown that we can count only on a comparatively small duration of heat sufficient to support such life as we are

now acquainted with on the earth. He finds that, 'By the most recent calculation, and taking into account all possibilities of greater density in the sun's interior and of greater and less activity of radiation in past ages, it would be rash to assume as probable anything more than twenty million years of the sun's light in the past history of the earth, or to reckon on more than five or six million years of sunlight for the future.'

The Moon.—The diameter of the moon is 2,160 miles or about $\frac{3}{11}$ that of the earth, hence it would take fifty moons to form a single body the same size as the earth.

Everyone knows that a ball of lead weighs more than an iron ball of the same size. Similarly, it has been found that the earth is 80 times heavier than the moon, although it is only 50 times larger; hence the materials which make up the moon must be lighter, bulk for bulk, than those forming our globe and in the proportion of 50 : 80, that is, the relative density or specific gravity of the moon compared with the earth is $\frac{5}{8}$. The earth's density is given as 5·58, hence the density of the moon is $\frac{5}{8}$ of $5{\cdot}58 = 3{\cdot}6$ —that is, the moon weighs about $3\frac{1}{2}$ times more than it would weigh if it were wholly composed of water.

Summing up these facts, we have :—

Diameter	2162 miles
Mass, in terms of the earth's mass	$\frac{1}{80}$
Volume „ „ volume	$\frac{1}{49}$
Relative Density, or Specific Gravity	3·43

General Appearance of the Moon.—The disc of the moon is variegated by irregular dark patches which have been imagined to have some resemblance to a human face. These dark and apparently smooth portions of the lunar disc were considered by early telescopic observers to be seas, and the brighter portions were thought to be continents. As the telescope was improved, however, the supposed resemblance between the earth and the moon was shown to be more fanciful than real, and we now know that the earlier astronomers' seas are almost as broken up as any other region. The lunar surface is covered with craters of extinct volcanoes, compared with which the volcanoes on our earth are pigmies. (Fig. 80.) We know the sun to be at a high temperature and self luminous; the surface of the earth is cool, but the temperature increases as we go down, showing that a high temperature exists in the interior of our globe; our satellite, however, seems to be a cold dead body. There is little

doubt that the moon, earth and sun at one time were all at the same temperature. The sun as it cooled threw off the earth, and the earth similarly threw off the moon. The three bodies are illustrations of the ordinary law of cooling; and for the same



Fig. 80. General appearance of the Moon in a small telescope. The top of the picture is the south.

reason that a large hot object takes much longer to cool than a small one, we find the temperature of that enormous mass, the sun, considerably higher than that of the earth, and the temperature of the earth much higher than that of its smaller companion the moon.

The Moon's Heat and Temperature.—Since the moon reflects the light of the sun it must reflect heat also, and one determination made the amount $\frac{1}{82000}$ of that received from the sun. Prof. C. V. Boys has made some determinations of the heat of the moon by means of an extremely sensitive arrangement. His instrument was capable of being affected by a candle-flame placed at a distance of nearly $1\frac{3}{4}$ miles, and it was found that the centre of the full moon reflected an amount of heat 4,800 times as great as could be observed with certainty. The dark part of the moon when a few days old gave no indication of heat. The temperature of the moon is most probably far below the temperature at which water freezes. As the sun's rays, however, strike on the lunar surface without being modified at all by passing through an atmosphere, the lunar surface must get much hotter, comparatively speaking; and recent determinations indicate that the temperature of the soil of the moon lit up by the sun is about that of the freezing point of water.

Influence of the Moon upon the Earth.—The most marked effects produced by the moon upon the earth are the tides. Certain fluctuations of terrestrial magnetism are also ascribed to lunar influence. But since the moon can raise the waters of the earth, it is natural to conclude that it has a disturbing effect upon the atmosphere, and therefore upon the weather. The effect is so small, however, that it is masked almost entirely by other atmospheric waves. A recent examination of barometric observations extending over a number of years seems to show that the moon lowers the height of the barometer from September to January at the time of full moon, and raises it during the first quarter. No effect is perceptible in other months.

Absence of Lunar Atmosphere.—No clouds are ever seen upon the moon. This in itself, indicates the absence of lunar atmosphere. It often happens that the moon passes right in front of a star, and the star is then said to be occulted, the occurrence being called an *occultation*. Observations show that a star does not fade slowly out of sight, nor does it undergo any apparent displacement, as it would do if an atmosphere surrounded our satellite, but disappears suddenly behind the moon without suffering the least displacement or fading. Such observations conclusively prove that the moon has no appreciable atmosphere, hence no water or other volatile fluid can exist there, and it must be as lifeless as an arid rock.

Further, the shadows of objects on the moon are black and sharp, and the objects themselves are never hazy. We can, therefore, sum up the observations which indicate that there is no air or water on the moon as follows:—

(1.) When the moon passes in front of a star, the star disappears instantaneously behind it and retains its full brightness right up to the moment of disappearance.

(2.) All parts of the moon appear equally sharp and well defined without any haziness.

(3.) No clouds are ever seen.

Lunar Maria or Seas.—The dark patches on the moon which were mistaken by early astronomers for seas, still retain that signification, though it is unquestionably known that they do not consist of water. Near the north-west edge of the moon is a large patch called Mare Serenitatis, or the Sea of Serenity. To the west of it occurs Mare Crisium, and to the east Mare Imbrium. Another conspicuous patch, Oceanus or Mare Procellarium, is found near the eastern edge. If these markings were really sheets of water, then when they are on the terminator, that is, on the line which separates the bright from the dark portion of the moon, their surfaces would appear as curved lines. Observations show that the terminator is broken by peaks and pits, and that the line does not follow a regular curve in any respect. It is probable that the 'seas' appear dark because the material of which that part of the lunar surface is composed has a smaller reflecting power than surrounding portions of the disc. There is every reason to believe that they are the beds of extinct seas and oceans.

Lunar Craters and Walled Plains.—The craters on the moon are very numerous and many of them very large. There are hundreds of craters as large or larger than the great lakes of molten lava in Hawaii, and dozens from fifty to one hundred miles across. In general, the craters are more or less circular and surrounded by a ridge. One or more conical peaks can usually be distinguished near the centre of the floor of the crater. To account for the ridges, it has been suggested that the conical peaks referred to are volcanic cones. When the volcanoes were in active eruption the ejected material was sent out with such a force that it did not accumulate round the vent, as in our terrestrial volcanoes, but fell at a distance from the vent and formed rings or ridges round it. Assuming that the cause of lunar

eruptions was the outburst of water-vapour, it is quite possible for such large rings to be produced, for the force of gravity at the moon is only one-sixth that at the surface of the earth, so volcanic products would be carried to a great distance before they fell. As the activity of the volcanic eruptions diminished, the materials began to collect round the vent and build up the cones and peaks which exist within the ridges. One of the most conspicuous craters on the moon bears the name of Copernicus. Its diameter is about 55 miles, and the average height of the top of the ring above the crater floor is about 11,000 feet. The heights of rings or peaks are obtained by measuring the lengths of their shadows. Near the south-east edge of the moon is a walled plain known as Schickard, which has a diameter of about 132 miles; Archimedes is a similar plain having a diameter of about 50 miles, the height of the top of the wall above the plain being about 600 feet. This is seen to the north-west of Copernicus. There seems to be a regular gradation between deep craters and walled plains, the difference between the two being merely one of depth.

Lunar Mountain Ranges.—On the earth the mountains, as a rule, run in ranges, and it is the exception to find them isolated. The reverse is the case on the moon. There are, however, a number of well-marked ranges on our satellite. One known as the Apennines has a length of nearly 500 miles, and on it exist peaks from 10,000 to 20,000 feet high. At the south edge of the moon occurs a remarkable range termed the Leibnitz Mountains. One of the peaks on this range reaches a height of 35,000 feet, and there are several more near it having heights not much less.

Valleys, Rills and Clefts.—A number of valleys or rills, some twenty miles wide and a couple of hundred miles long, others much smaller, both in length and breadth, are seen upon the moon. They probably represent the valleys of extinct rivers. A powerful telescope shows also nearly a thousand narrow clefts cutting through craters and valleys and anything else in their way.

Rays and Ray-systems.—Bright streaks or rays radiate from a few of the craters and cut through mountains and valleys like the clefts described above. The crater known as Tycho possesses the most conspicuous of these ray-systems. It is situated near the southern edge of the moon. At the time of full moon the markings are very plainly visible, and Tycho then looks like the top of a peeled orange. Several explanations have been suggested to account for clefts and rays, but none can be considered very satisfactory.

QUESTIONS ON CHAPTER VIII.

1. How have the direction of the sun's axis in space and the period of rotation been determined? (May, 1891.)

2. What terrestrial phenomena seem to be connected with the number of spots seen on the sun at different times? (May, 1879.)

3. What are the facts which lead us to suppose that the moon has no atmosphere? (May, 1890.)

4. What conclusions concerning the origin of the physical features of the moon have been deduced from its telescopic appearance? (May, 1877.)

5. State what you know about sun spots.

6. What is a sun spot, and how are sun-spots distributed on the sun's disc?

7. Describe the changes which take place on the sun during a sun-spot cycle.

8. What is the physical nature of sun-spots, photospheric clouds or rice-grains, granules, and faculæ?

9. Describe a method of determining the intensity of solar radiation.

10. Discuss the apparent connection between sun-spots and magnetic storms.

11. Enumerate the most conspicuous features seen upon the moon by means of a telescope.

12. What is known concerning the temperature of the moon?

CHAPTER IX.

PLANETS AND SATELLITES.

We have described the movements of the planets and satellites of our solar system, and the means by which the characteristics of these bodies can be investigated. In this chapter we shall deal chiefly with the results obtained. The planets of which we know most are Mars, Jupiter, and Saturn. Mercury and Venus are so near the sun that the markings upon their surfaces are almost drowned in the sun's rays; Uranus and Neptune are so far away that markings upon them are almost indistinguishable. However, we will consider all the planets in their order of distance from the sun, calling special attention to any peculiarities which they may possess. The comparative diameters of the planets are shown in Fig. 81.

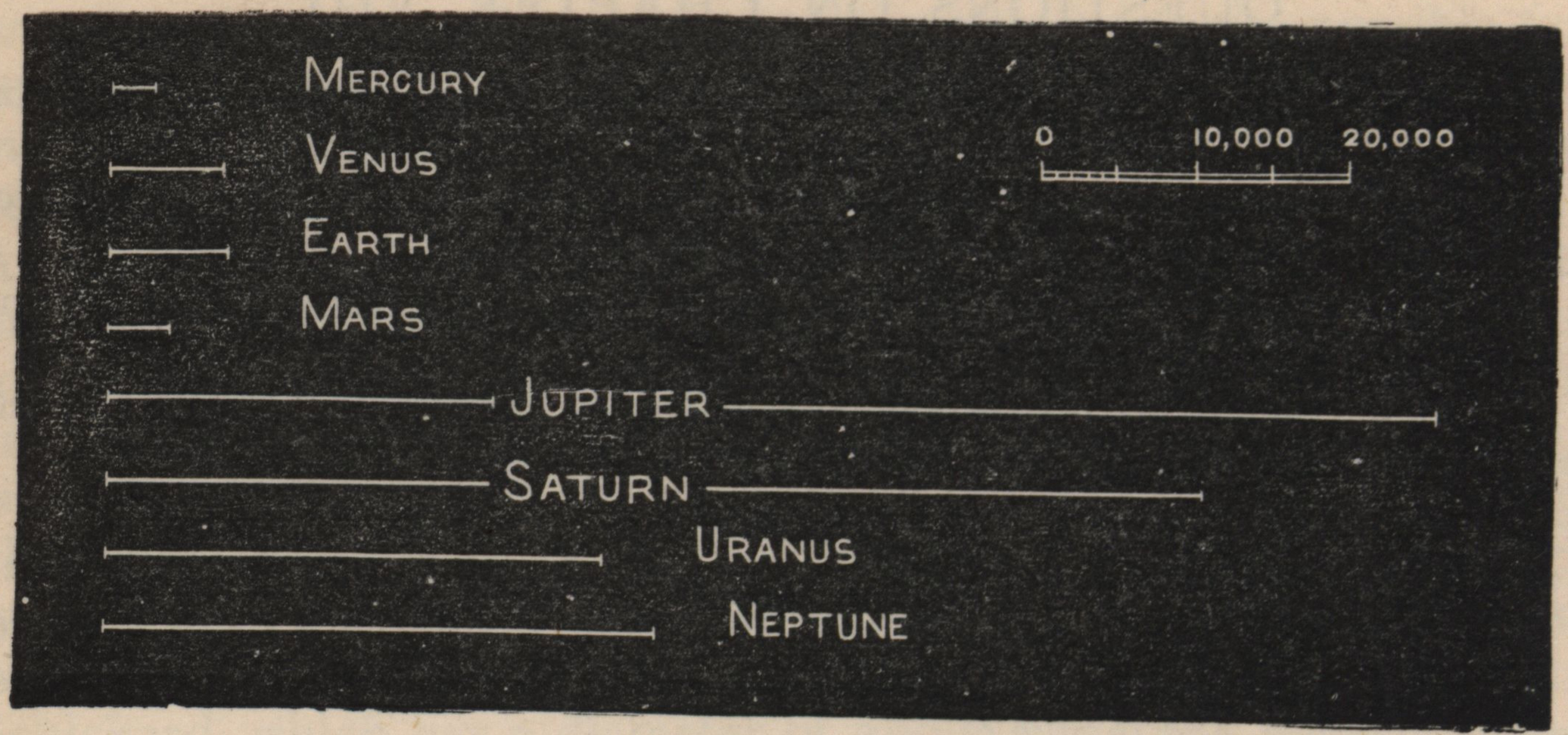


Fig. 81. Comparative Diameters of the Planets.

Mercury is the nearest planet to the sun. Its mean distance is 36,000,000 miles, but because of the great eccentricity of its orbit the actual distance ranges from 28,500,000 to 43,500,000. The sidereal period of the planet is nearly 88 days, and the synodic

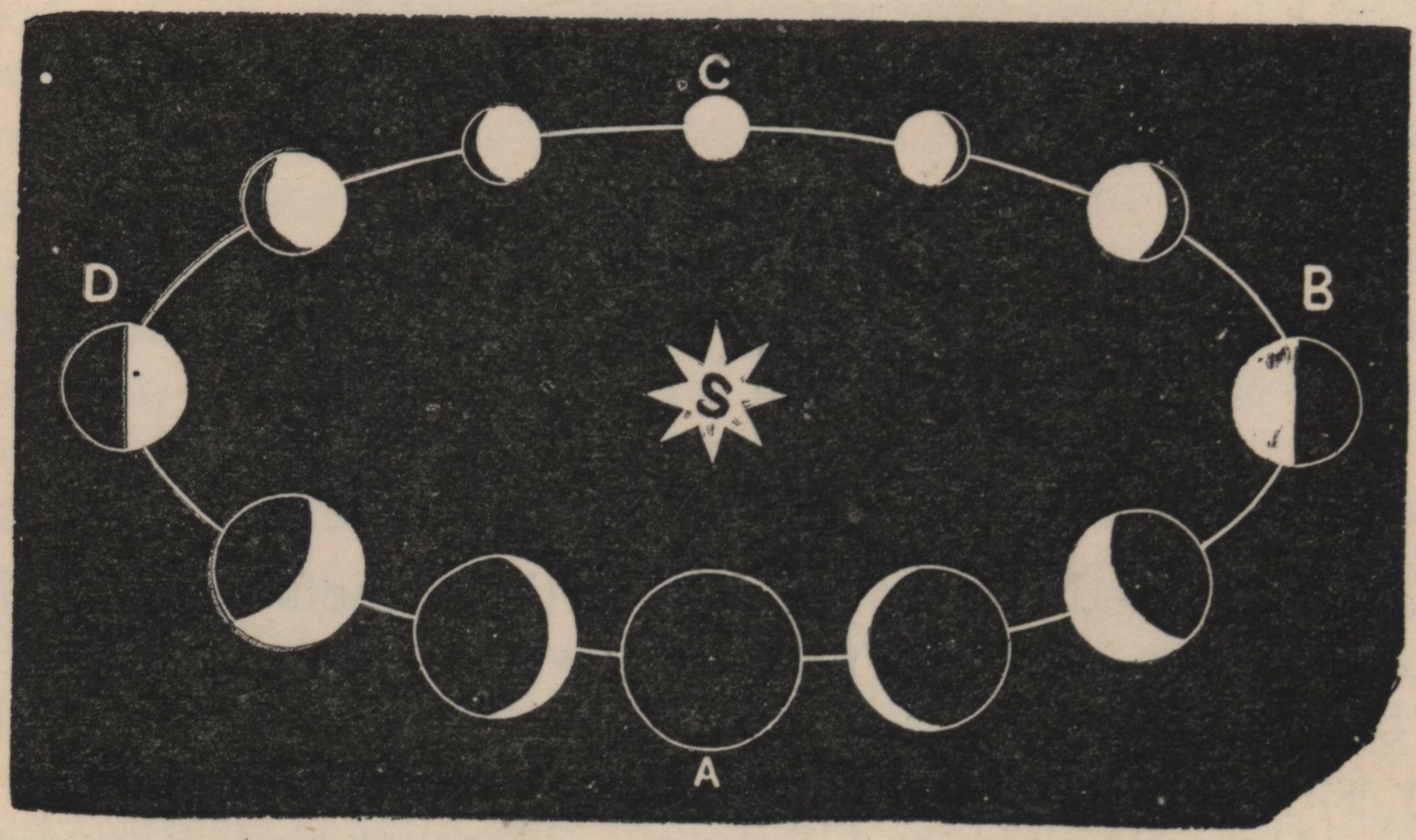


Fig. 82. Phases of Mercury. A & C represent the positions at inferior and superior conjunction respectively.

period is 116 days. Its diameter is about 3,000 miles, it weighs about one-eighth as much as the earth, and is about 12 times as heavy as a globe of water would be of exactly the same size. Both the planets between the earth and the sun, *i.e.*, Mercury and Venus, go through the same changes as the moon. The cause of

these changes will be seen from an inspection of Fig. 82. Sometimes Mercury comes directly between the earth and the sun, and may be seen by means of a telescope to cross the disc of our luminary as a small black spot. This is called a transit of Mercury, and occurs at certain definite intervals of time. The time of rotation on its axis is not yet known with any degree of accuracy. In 1889 an astronomer named Schiaparelli published observations which seem to indicate that the planet revolves on its axis in the same time that it takes to go round the sun, viz., 88 days. Previous to this, it was supposed to be about 24 hours. From this uncertainty, it will be at once concluded that the surface markings of Mercury appear very faint; indeed, a good eye is required to notice anything, except that the edge of the planet is brighter than the central portion. There is evidence that the planet has a slight atmosphere around it in which water-vapour exists. No satellite has been discovered circling round Mercury, and there is very little probability of one ever being found.

Venus is, next to the sun and moon, the most brilliant object in the heavens. It goes through the same changes as Mercury and the moon. Accordingly it sometimes rises just before the sun as a 'morning' star, or sets just after the sun, when it is said to be an 'evening' star. The cause of these different appearances is shown in Fig. 83. Occasionally the planet passes between the sun

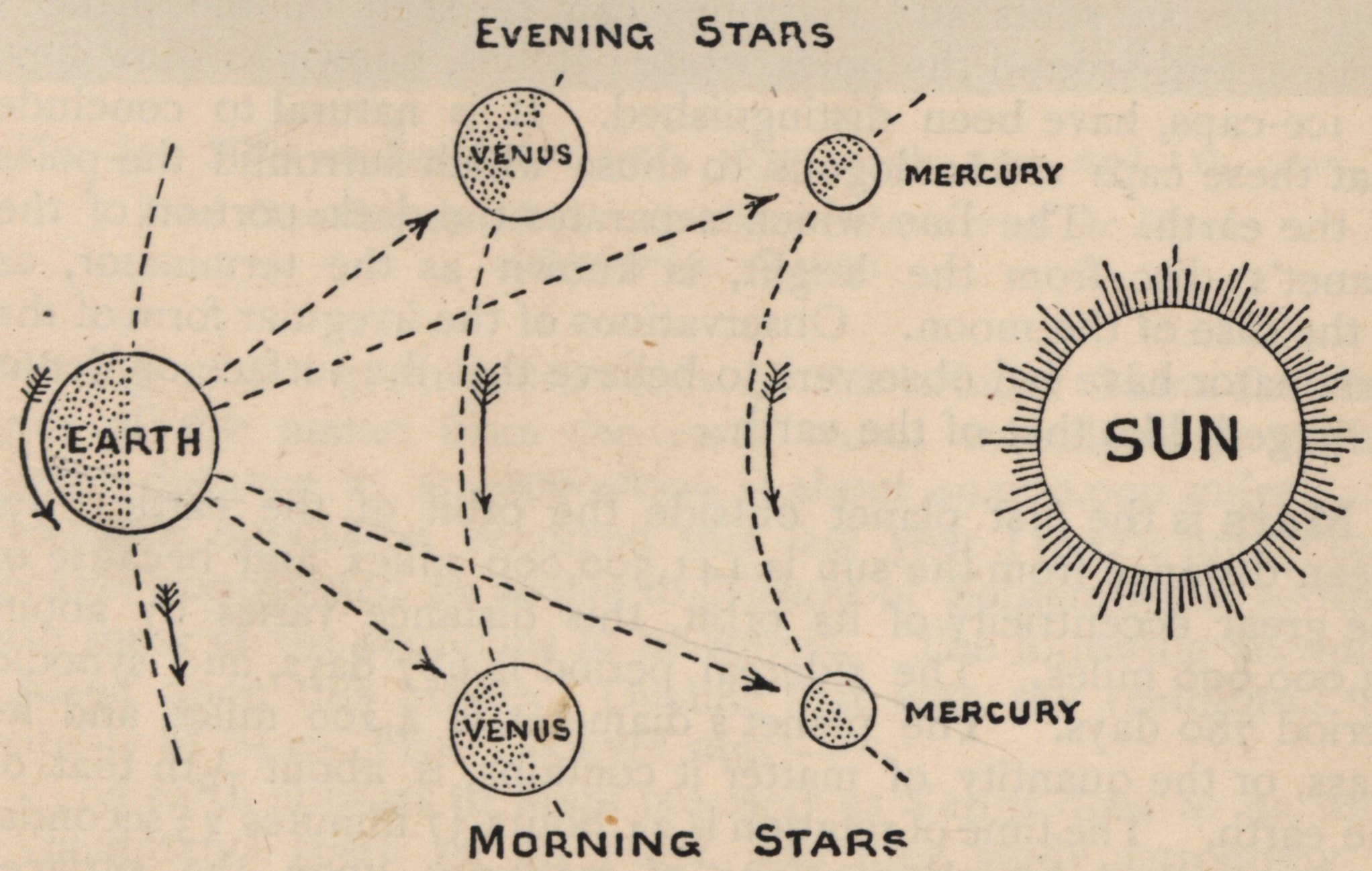


Fig. 83. Venus and Mercury as Morning and Evening 'Stars.'

and the earth, and is visible as a black spot upon the sun's disc. This is a transit of Venus, and occurs at alternate intervals of 120 and eight years. The sidereal period is 225 days, and the synodic period 584 days. The mean distance of Venus from the sun is 67,200,000 miles, and, owing to the small eccentricity of its orbit, the greatest and least distances only differ from this by about 470,000 miles. Its mass is about four-fifths that of the earth, its diameter is about 7,700 miles, and it would weigh about five times as much as an equal globe of water. The period of rotation has been stated as nearly 24 hours, but Schiaparelli has brought forward evidence to prove it to be equal to its revolution period, that is, 225 days.

Just before a transit of Venus, a thin circle of light is seen round the planet. A similar line of light has also been noted when the planet is very near conjunction. The phenomenon is produced by the refraction of sunlight in the atmosphere of Venus, which is probably twice as dense as the atmosphere of the earth. The spectrum of Venus, though on the whole but a reflected solar spectrum, shows undoubtedly the presence of water-vapour. Sunlight falls upon the atmosphere, and much of it is reflected to us from the outer surface, but some penetrates the atmosphere and only reaches us after sinking in and being reflected back. In traversing this thickness, absorption occurs, and the spectroscope reveals the kind of absorption. Under favourable circumstances, faint, greyish spots and markings can be seen on the planet's surface, and around the poles, white patches, known as snow-caps or ice-caps, have been distinguished. It is natural to conclude that these caps are analogous to those which surround the poles of the earth. The line which separates the dark portion of the planet's disc from the bright, is known as the terminator, as in the case of the moon. Observations of the irregular form of the terminator have led observers to believe that the surface of Venus is rugged, like that of the earth.

Mars is the first planet outside the orbit of the earth. Its mean distance from the sun is 141,500,000 miles, and because of the great eccentricity of its orbit, this distance varies by about 13,000,000 miles. The sidereal period is 687 days, and synodic period 780 days. The planet's diameter is 4,200 miles, and its mass, or the quantity of matter it contains, is about $\frac{1}{10}$th that of the earth. The time of rotation is 24 hours 37 minutes 23 seconds, as determined by observations of markings upon the surface.

(Fig. 84.) Deposits of ice and snow are seen at each pole of this planet; these deposits alternately diminish and increase as the north and south poles approach the summer and winter solstices. This is analogous to what occurs on the earth, and demonstrates the presence of considerable quantities of water-vapour in the Martian atmosphere. Two small satellites were discovered in 1877 to revolve round the planet; they can only be observed, however, with very powerful telescopes.

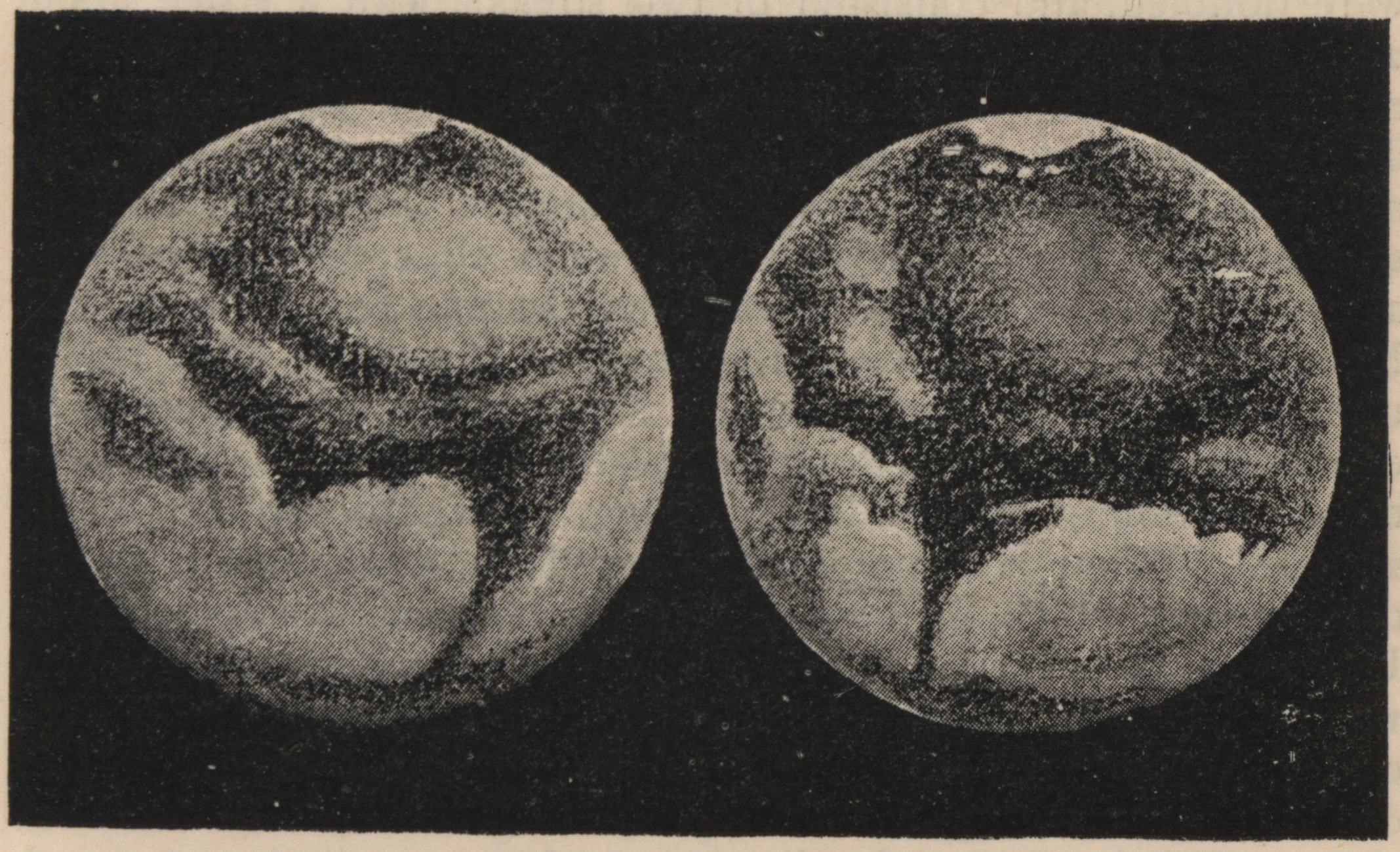


Fig. 84. Mars on September 10th, 1877, at 9h. 15m. and 11h. 20m.

From Drawings by Mr. N. E. Green (Memoirs of the Royal Astronomical Society).

Owing to the great eccentricity of the orbit of Mars, the distance of the planet from the earth varies considerably. The average distance at an opposition is about 49,000,000 miles. A favourable opposition occurred this last year (1892), and Prof. Lockyer contributed an article to *Nature* of September 8, setting forth some of the problems to be solved. The following account is based upon this article. Dealing first with the conditions of visibility of Mars, Prof. Lockyer says:—

'The earth appears to Mars precisely as Venus does to us, and if inhabitants there be on Mars, and they study astronomy a transit of the earth to them will be what a transit of Venus is to us.

Further, as we see Venus as a half moon, and when nearer to us as a fine large crescent, so the Martians, as the earth approaches them, will see her as a half moon and then as a crescent, getting finer as the apparent diameter of the completed circle gets greater.' During the opposition of 1877, the Italian astronomer, Schiaparelli, discovered a number of streaks, most of them very long and very straight, running across the land surface of Mars. Many of these streaks are 1,000 miles long and 200 miles wide. In 1882 the same astronomer found that in at least twenty cases the channels were doubled, and consisted of two streaks, with a space about 200 or 300 miles between them. This doubling or 'gemination' of the channels appears to be connected with the planet's seasons. The existence of some of these mysterious markings has been confirmed during the recent opposition. Professor Lockyer suggests that 'the channels are true water channels; at one time at low channel we may have an unimportant stream like the low Nile; at another an ancient river-bed, as it were, is filled to the utmost limit by the inundation . . . and in my mind there is no doubt whatever that the doubling is due to cloud banks lying, or rather travelling, longitudinally along the centre of the water-surface.' When Schiaparelli discovered the channels he named them *canali*, which in Italian means a channel, canal, or a pipe. Upon the discovery being translated into English, the word canal was used, which suggests human labour, so it was inferred that our ruddy brother had inhabitants like ourselves, and the doubling of the canals was suggested to represent signals from the Martians to us. This has led to the discussion of the possibility of signalling to Mars. A few years ago it was proposed to communicate with the inhabitants of the moon by establishing fire-signals in the shape of circles, triangles, etc., upon the Plains of Siberia or the Sahara Desert, to which signals the Lunarians would reply, if they saw them. If there were any inhabitants upon our satellite —a supposition not at all likely—the problem would arise of bridging the trifling chasm of 240,000 miles which separates them from us. But now it is Mars with which we wish to communicate and the planet is never less than 35,000,000 miles from us. Several methods of signalling have been suggested, all more or less impracticable. A number of mirrors were to be arranged so as to flash simultaneous beams of sunlight towards the planet; but this would require the object to be visible towards which the flash is directed, and Mars is not visible to the naked eye at day. Another suggestion is to get the gas companies to alternate

darkness and light over the whole of London at intervals of five minutes during certain hours of the night; but gas jets would require to be very bright and powerful indeed to produce any effect at such an enormous distance. A still better idea would be to get all the navies in the world collected in one place to flash their search lights simultaneously towards the planet; or a specially devised electric search light of enormous candle power could be used for the same purpose. Many other suggestions have been made by seekers after 'other worlds than ours,' but there is little doubt that some centuries will pass before any system of earth-signalling is attempted.

The Minor Planets or Asteroids.—Kepler noted that the mean distances of the planets from the sun seemed to be connected by some simple law of progression. The publication of Bode's empirical law in 1772 confirmed Kepler's views, and fixed the distance of the hypothetical planet as 2·8 times the mean distance of the earth from our luminary. And the existence of such a planet appeared still more probable when calculations showed that the mean distance of the planet Uranus, discovered by Sir William Herschel in 1781, might have been predicted with accuracy from Bode's Law. At a Congress held Gotha in 1796, it was proposed to search for the unknown body, and twenty-four astronomers each undertook the observation of a portion of the ecliptic. On January 1, 1801, almost before the association of observers had got fairly to work, a small object was discovered by Piazzi. Calculations proved that the mean distance of this body from the sun is 2·77, which corresponds with that indicated by Bode's Law, hence the gap appeared to be filled, but by a body of very modest size, for its diameter was found to be only about 155 miles. The body discovered by Piazzi was named Ceres. A second body was afterwards found to be revolving round the sun at about the same mean distance as Ceres. This put a new aspect on the question. The two bodies may pass very near to each other at the two points situated on the line of intersection of the planes of their orbits. This led Olbers to believe that the new planets were portions of a larger body broken up by some internal disturbance, and he accordingly suggested that other fragments might be found near the points of intersection in question. The hypothesis was given support by the discovery of Juno in 1804 near one extremity of the line, and the discovery of Vesta in 1807 close to the other extremity. It was not until 1845 that a fifth minor planet was discovered, and this was even smaller

than the four that preceded it. After this date the discoveries became more frequent, and now the number known is about 380. But the magnitudes of the newly-discovered bodies are decreasing, for, while the first four have magnitudes comprised between 6 and 8, those now discovered are rarely brighter than the 13th magnitude. The hypothesis advanced by Olbers as to the origin of the *asteroids*—a designation due to Herschel—has not found much support. Newcomb, from an investigation of the orbits of the first forty asteroids, found that their planes were far from having the common line of intersection which they should have if the bodies represent parts of an exploded planet. It may be suggested that the conditions were fulfilled at a certain epoch, and that the perturbations caused by Jupiter and Saturn have brought about the present distribution. Calculations show, however, that the required condition never existed, hence Olbers' hypothesis must be abandoned. The asteroids have become so numerous that it is usual to distinguish them by numbers, surrounded by a circle in this manner (25), the name often being omitted.

Some asteroids are useful on account of their near approach to Jupiter. Of these (279) is of special interest, for in 1912 it will be at the same distance from Jupiter as the earth is from the sun. At this time the attraction of Jupiter on the asteroid will be more than $\frac{1}{50}$ that of the sun, and from observations of the perturbations that must ensue, the mass of Jupiter can be determined with considerable precision. The asteroids having orbits near the inner limit of the ring are also useful, especially if their orbits are very eccentric, and they approach the earth within 0·7 its mean distance. In such cases their parallax can be very accurately determined by observations made at two stations some distance apart. From the parallax obtained, the parallax of the sun can be deduced. Indeed, this is one of the best methods at our disposal for determining solar parallax. With regard to the sizes of the asteroids, the largest cannot be more than 300 miles in diameter, and some are probably no more than 10 miles, whilst the whole lot now known have only a bulk about $\frac{1}{4000}$ that of the earth.

Jupiter is the largest of the planets, its bulk being about one and a half times greater than all the rest put together. It circles round the sun at an average distance of 483,000,000 miles, that is, in an orbit having a diameter a little more than five times greater than the path of the earth. The eccentricity of Jupiter's orbit is

·0482, whilst that of the earth's orbit is only ·0167. On account of this very definite departure from a circle, the actual distance of Jupiter from the sun varies a little more than 21,000,000 miles on each side of the mean distance. The orbital velocity of the earth is eighteen miles per second, whilst Jupiter only accomplishes eight miles in the same time. In consequence of this slower rate of motion and increased length of path, the planet takes 4,332·6 days or 11·86 years to make a circuit of the heavens, but only 399 days to make a synodic revolution, that is, to pass from opposition to opposition, as seen from the earth.

The polar diameter of Jupiter has a length of 83,000 miles, whilst the equatorial diameter is 88,200 miles, a difference from which an oblateness or ellipticity of $\frac{1}{17}$ is derived, whilst that of the earth is only $\frac{1}{294}$. The mean diameter is 86,500 miles. From this we see that eleven earths in a line would just about stretch from one side of this stupendous globe to the other. The disproportion between the two Jovian diameters is a feature easily observed. Utilising the measurements given above, it may be found by calculation that the surface of Jupiter is 119 times greater than the area of the earth. And the volume is 1,300 times greater; in other words, 1,300 globes having the same bulk as the earth would be required to form one body as large as Jupiter. If the materials of which Jupiter is composed were in the same condition as those which make up the earth, it is evident that this planet should be approximately 1,300 times heavier than the earth. But this is not so. Were it possible to place Jupiter in one scale-pan of a balance and weigh it against the earth, we should find that about 316 earths would be necessary to counterpoise it. In other words, if the earth in its present condition were as large as Jupiter, it would be four times heavier. The mean density of Jupiter is therefore one-fourth that of the earth; in fact, it is very nearly equal to the density of the sun, and a little greater than the density of water.

And yet, in spite of this low density, Jupiter has a mass so great that twice the mass of all the other planets put together is hardly equal to it. The mass of Jupiter is known with a greater degree of accuracy than that of any other planet. It has been determined from observation of the motions of each of the four satellites which circle round him; and from observations of his perturbing effect upon the paths of some of the minor planets which circle between him and Mars, and the comets which come within his sphere of attraction.

In even a small telescope this ponderous body is a fine object to observe, and with a large instrument he is seen to be traversed with belts of cloud above and below his equator, and more or less parallel to it, and covered with numerous delicately tinted spots and markings. A red-coloured spot appeared on the planet about

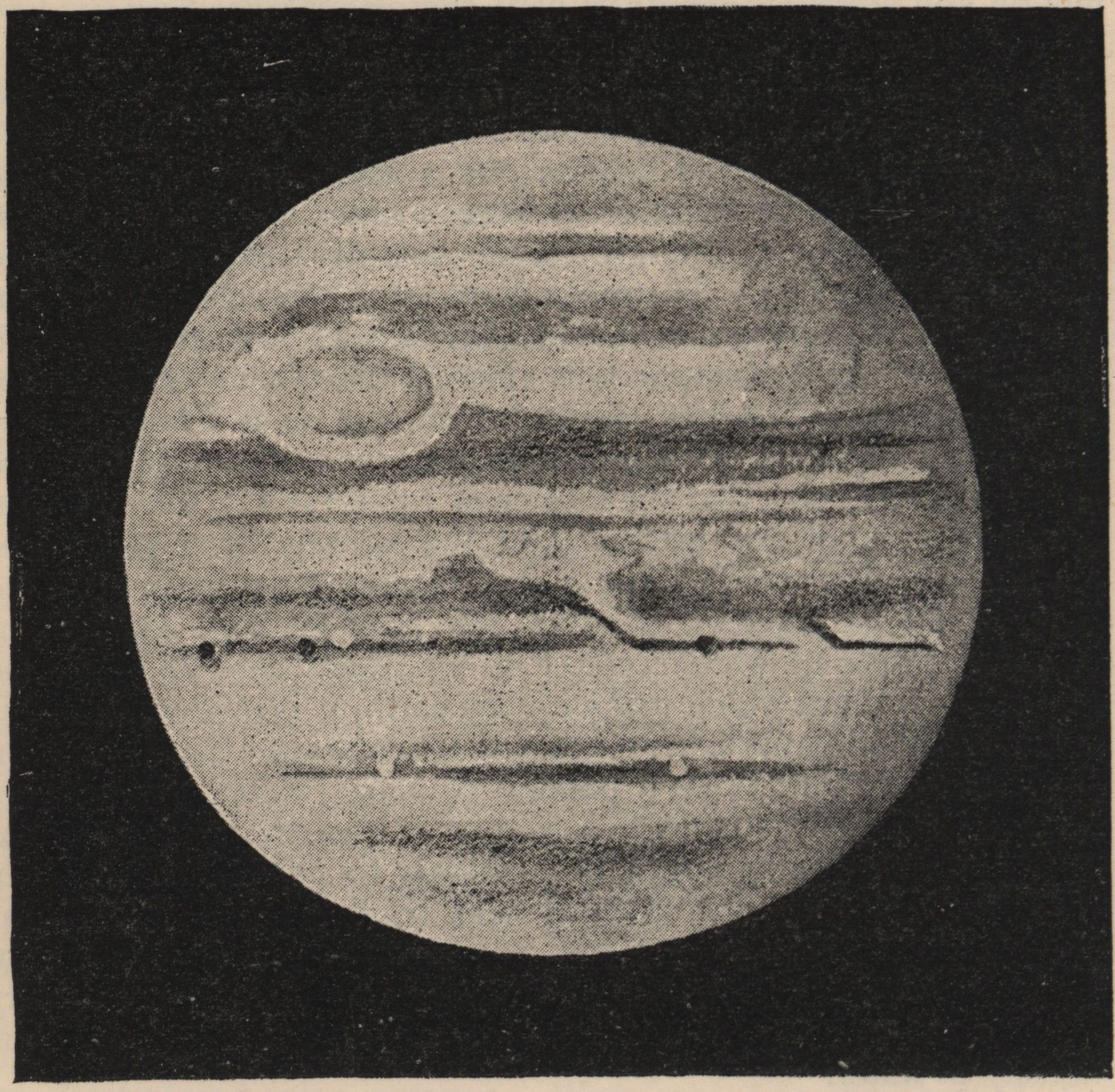


Fig. 85. Jupiter, July 30th, 1890, showing the red spot.

From a Drawing by Professor Barnard. (*Monthly Notices of the Royal Astronomical Society.*)

thirteen years ago, and has been observed as a very striking object ever since. It was noticed as a remarkable feature in July, 1878, but most probably existed as a less conspicuous object long before. It is constantly elliptical in outline, but has exhibited various

changes of colours, from brick-red to a light tint differing very little from the surrounding portions of the planet's disc. At the present time the 'great red spot' is well defined and fairly visible. The spot is doubtless a depression in the planet's atmosphere, for at times layers of cloud overlap and partially obliterate it. (Fig. 85.)

When the belts are observed for an hour or so they and the spots and various markings may be seen to change their position on the visible disc. The portions of the belts near one edge of the planet at the commencement of the observations will have disappeared, and new features will have appeared at the opposite edge. By observations of the rate of movement of particular spots, it is found that the planet is in rapid rotation, and whirls completely round on his axis in a little less than ten hours. When we consider that in consequence of the earth's axial rotation a point on the equator has a velocity of 1,000 miles an hour, and that Jupiter's diameter is eleven times longer than the earth's, it follows that a point on the Jovian equator possesses a velocity twenty-seven times greater than one similarly situated on the earth. It is on account of the high centrifugal force thus called into play that the oblateness of the planet is so considerable.

The intensity of the sun's heat received by Jupiter is only $\frac{1}{27}$ of that intercepted by the earth. This amount is quite insufficient to produce the cloud-belts, or cause the swift transformations which are often observed in them and other markings. There is, therefore, little doubt but that Jupiter emits a certain amount of light and heat of his own, in addition to the reflected sunlight, of which his luminosity mainly consists. This idea also finds support in the low density of the planet and his rapidity of rotation. The probability is that our giant planet is nothing more than a globe of fluid overlaid by the dense clouds above described. It is not self-luminous to any appreciable extent, for its spectrum differs very little from that of reflected sunlight. Countless ages ago the earth must have been in the same heated and semi-fluid condition as Jupiter is now; but owing to its being much smaller it has cooled down quicker. In the distant future the mighty orb will condense to the condition of the earth, and our globe itself will then roll through space a cold and arid rock, like the moon.

In 1610 Galileo discovered four moons revolving round Jupiter; they can easily be seen with a good field glass. It is

usual to distinguish these bodies by the Roman numerals, I., II., III., IV., counting from Jupiter. The following numbers refer to Jupiter's satellites :—

Satellite.	Distance in Miles.	Period. d.	h.	m.	s.	Diameter in Miles.
I. Io	261,000	1	18	27	33	2,500
II. Europa ...	415,000	3	13	13	42	2,100
III. Ganymede ...	664,000	7	3	42	33	3,550
IV. Callisto ...	1,167,000	16	16	32	11	2,960

In 1892 Prof. Barnard, using the Lick Telescope having a diameter of 36 inches, discovered a new satellite of Jupiter. With regard to its faintness, he remarked,—'It is scarcely probable that the satellite will be seen with anything less than twenty-six inches, and only with that under first-class conditions.' Measures were made of the elongations of the satellite, and the following values obtained :—

	From Jupiter's centre.
Eastern elongation	$48''.089$ = 112,500 miles.
Western „	$47''.621$ = 111,412 „

From these the period was derived, using the Harmonic Law,

$$P = p \sqrt{\frac{m}{M}} \frac{R^3}{r^3}$$

where P, M, and R are the period, mass and mean distance of Jupiter, and p, m, and r represent corresponding terms for the satellite.

The mean value found for the period is 11h. 57m. 23·06s. It appears, therefore, that the satellite goes round the planet twice in less than twenty-four hours.

Jupiter's satellites are often seen projected as spots upon the planet's disc, they are also observed to pass into the shadow of the planet and be eclipsed. It will be remembered that eclipses of Jupiter's satellites led to the determination of the velocity of light.

Saturn is the remotest of the planets known to ancient astronomers. Its mean distance from the sun is 886,000,000 miles, with a variation of nearly 50,000,000, on account of the eccentricity of its orbit. The sidereal period is $29\frac{1}{2}$ years, and the synodic period 378 days. This planet differs from all the rest in being surrounded by a system of rings, in addition to eight satellites.

The planet's polar diameter is 68,000 miles, and equatorial diameter 75,000 miles, this gives a mean diameter of nearly 71,000 miles, and therefore the volume of the planet is nearly 740 times that of the earth; the mass, however, is only 95 times that of the earth, hence the materials of which it is made up are only $\frac{1}{8}$ as dense as those forming the earth. Cloud belts running parallel to the equator are seen on this planet as on Jupiter, but they are not so well marked nor so variable in character. The spectrum of Saturn, like that of Jupiter, shows several dark bands in the red, but the nature of the substances producing this absorption is unknown. The time of rotation on its axis is about 10 hours 14 minutes. A view of Saturn is shown in Fig. 86.

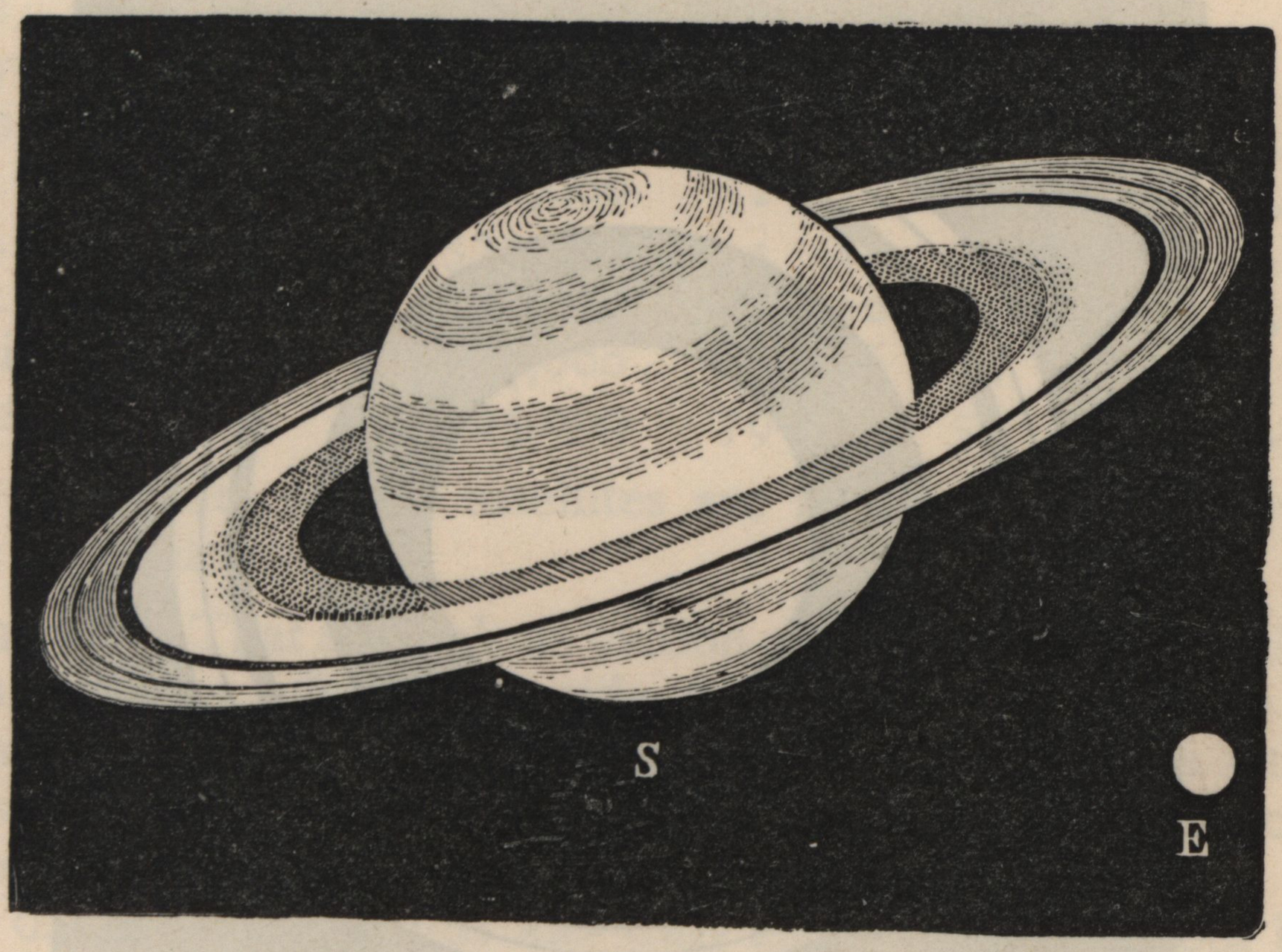


Fig. 86. View of Saturn. The small disc E represents the earth.

Three separate rings are now known to surround Saturn, the diameter of the outermost edge of the whole ring system being about 168,000 miles. The ring nearest the planet is semi-transparent, and is known as the gauze ring, or dusky ring. The dimensions of the rings are shown in the following table :—

Outer edge of outer ring...	167,000	miles in diameter.
Inner " " ...	147,000	" "
Width...	10,000	miles.

Between the outer ring and the middle ring a gap of about 1,500 miles occurs.

Outer edge of middle ring...	144,000 miles in diameter.
Inner „ „ ...	110,000 „ „
Width...	17,000 miles.
Inner edge of dusky ring...	91,000 miles in diameter.
Width...	9,000 miles.

Between the dusky ring and the planet's surface a gap of about 9,500 miles occurs. Fig. 87 shows the view of the rings which would be obtained if observed from a point perpendicular to their plane.

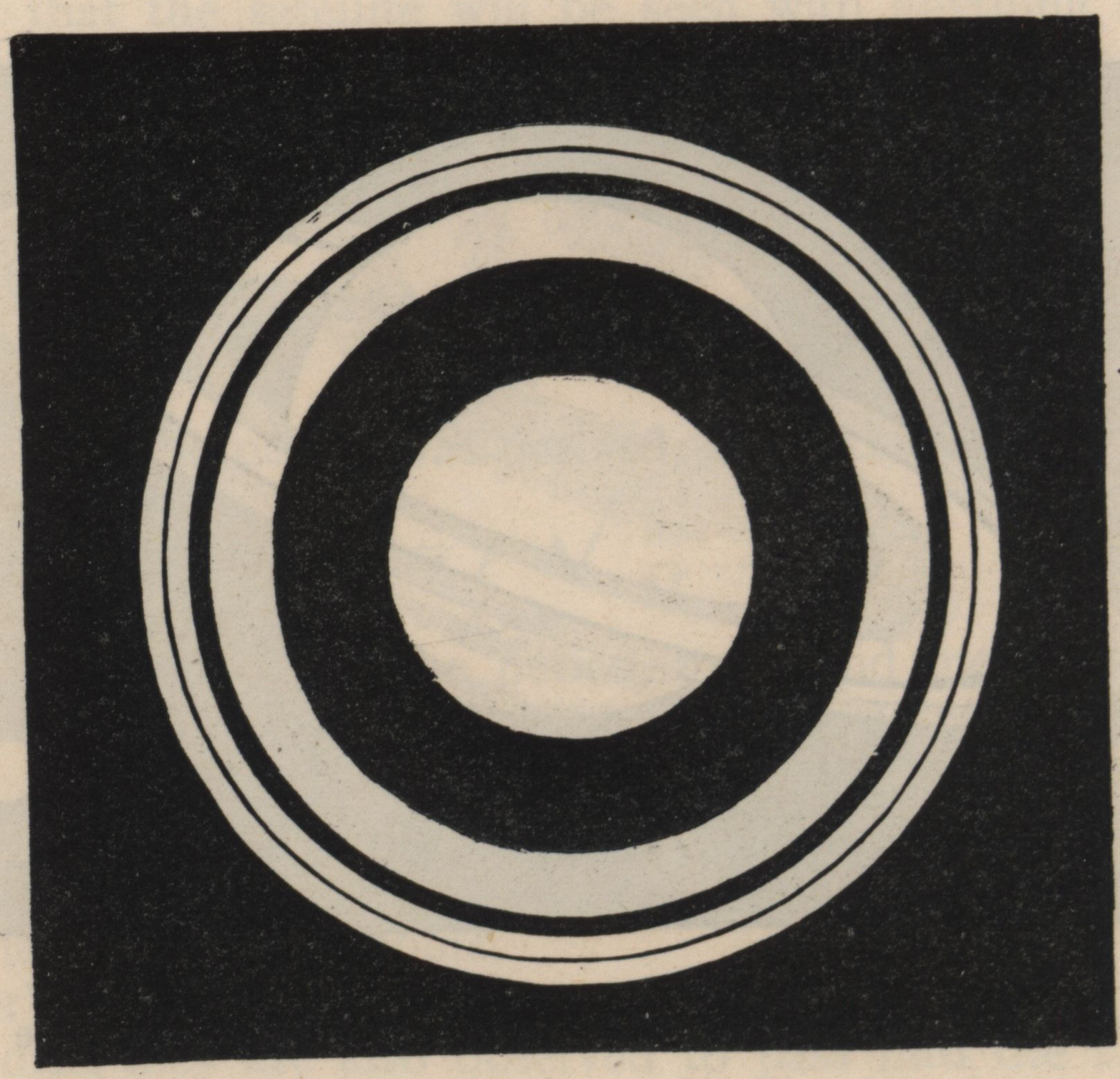


Fig. 87. Plan of Saturn and his rings.

The thickness of the ring varies at different parts, but does not exceed 200 miles in any place. When this number is compared with the enormous dimensions of the rings, an idea as to the flimsiness of the system is obtained. Viewed telescopically, the rings appear like solid material surrounding the planet. But a consideration of the conditions under which they exist leads at once to the conclusion that they cannot be solid, neither can they be

liquid, for tidal action would soon break them up. It is now universally accepted that the rings are made up of an infinite number of separate particles—a ring of meteorites—revolving round the planet in the plane of the planet's equator.

The plane of Saturn's equator, and, therefore, the plane of the rings, is inclined about 28° to the ecliptic. As in the case of the earth's equator, this inclination is practically constant. Hence it happens that sometimes we see one side of the ring, sometimes the other side, and occasionally the edge is presented to us. This occurs at intervals of about 15 years.

Saturn has eight satellites, their names and elements being as follows:—

Satellite.	Distance in Miles.	Period. d.	h.	m.	s.	Diameter in Miles.
Mimas	117,000	0	22	37	5	600
Encelydas	157,000	1	8	53	6	800
Tethys	186,000	1	21	18	25	1,100
Dione	238,000	2	17	41	9	1,200
Rhea	332,000	4	12	25	11	1,500
Titan	771,000	15	22	41	23	3,500
Hyperion	934,000	21	6	39	27	500
Japetus	2,225,000	79	7	54	17	2,000

The diameters of the satellites are not known with any great degree of accuracy.

Uranus.—That anomalous section of our solar system, Uranus and its satellites, offers yet a wide field for investigation to astronomical specialists of all kinds. Its figure, its rotation, its satellites and its physical constitution, are still moot points which can be more or less settled as our optical powers increase.

The discovery of Uranus was truly an acquisition to our knowledge. Observations of the ancient planets date back to time immemorial, but here was a 'wanderer' which the most perspicacious of astronomers had overlooked for ages. It was on March 13th, 1781, when that illustrious astronomer, Sir William Herschel, was surveying the stars in Gemini, this being part of his self-appointed task to survey the whole heavens and observe the character of all contained therein, that an object came into his field of view which his discriminating eye at once marked out as different from its companions. The telescopic appearance of a star, whatever its magnitude may be, is but a more or less brilliant point of light. The object that came within Herschel's

'ken,' although extremely faint, had an appreciable disc under the magnifying power of 270 which was being used. The crucial test was to use eye pieces of higher powers and to observe whether the disc underwent proportional magnification. This was done with powers of 460 and 492, the disc of light was sensibly magnified with each, although surrounding stars remained as points of light, and hence the differentiation was complete. Further observations of the position of the object relative to stars near it proved that it was in motion and belonged to our system. Astronomers, in their philosophy, did not then dream of the existence of another planet, and Herschel concluded from the appearance and the motion of the object that it was a comet at aphelion and announced his discovery as such to the Royal Society. Continental astronomers at once set to work to observe the position and compute the elements of the orbit of the supposed comet. Many different paths were assigned to it by many different computors, but since they were built upon a false assumption the estimated and real positions of the object were strikingly different, and its erratic motion seemed to defy delineation. It was then pointed out that if the body were a comet its perihelion distance would have to be at least fourteen times the radius of the earth's orbit, a conclusion which at once opened the way for new ideas, for by analogy it had been concluded that the perihelion distance was certainly not beyond the orbit of Jupiter and was most likely situated within the earth's orbit. Maskelyne appears to have first suspected the planetary nature of the body, but it was Lexell who calculated a circular orbit for it. This observer happened to be in England at the time of the discovery, and by using two extreme observations of known position, one made by Herschel on March 17th, 1781, and another by Maskelyne on May 11th of the same year, he found that the orbit was probably circular, with a radius about eighteen times greater than the mean distance of the earth from the sun. This computation, however, still carried with it a certain amount of error which it was desirable to eliminate, and it was Laplace, in 1786, who finally declared the true path to be elliptical, as the other planets, but with a very small eccentricity, about 0·046.

Having determined the planet's path, astronomers assumed, and such assumption is the soul of investigation, that Uranus had most probably been recorded as a star in former star-maps. A search proved the conclusion to be a right one. Flamsteed in his 'Historia Cœlestis' recorded in 1690 a sixth magnitude star in a part of the heavens which it was shown Uranus had occupied

The fact that no such star was visible in the place Flamsteed had recorded it could lead but to one conclusion, viz., that Uranus had been unwittingly catalogued as a star, and we find, even in 1784, three years after the discovery of Uranus, a paper by Le Monnier in the Montpellier Memoirs: 'Sur la disparition *de l'etoile* de la constellation du taureau, que Flamsteed a placée dans son catalogue pour 1690 a 51° 48′ 50″ de longitude, avec une latitude de 0° 5′ 15″ meridionale,' in which he treats of the disappearance of a star which Flamsteed had observed. This star was Uranus, and although Flamsteed observed it several times between 1690 and 1715, its planetary appearance was not recognised. Eighteen times was the planet recorded as a star before Herschel's discovery of its true character on his first observation of it. The fact of these negative observations alone stands out as a monument of Herschel's discrimination and ability. Bradley, Mayer, and Le Monnier all unconsciously observed Uranus and passed it by without comment. Indeed, Le Monnier himself made no less than nine observations of Uranus, many of them following each other night after night in a regular sequence, and yet did not notice the change of position which the planet must have undergone. This was not very remarkable, for Bouvard found one of the observations of Uranus on an empty hair-powder bag, and Arago stigmatises them as 'the image of chaos.' Le Monnier had evidently taken to mind Captain Cuttle's advice: 'When found, make a note of.' But such notes, unmethodically arranged, are as bad as no notes at all when astronomical work is concerned, for by not arranging them decently and in order Le Monnier lost immortality.

The new member of our family had been assigned a place. The ingenuity of astronomers was now exercised in selecting an appropriate name wherewith the planet should be designated. The right of appending a name to his discovery really rested with Herschel and he exercised that right by suggesting *Georgium Sidus*, in honour of his patron George III. Were it not for the objections raised by continental astronomers this monarch had indeed bought honour cheap. Lalande said *Herschel* would be a more appropriate name, and the planet is often identified with this now. The discussion waxed warm over the respective merits of *Neptune*, *Astrea*, *Cybele*, with a host of others conjured up for the planet's signification. It was Bode who advanced the claims of *Uranus*, the father of Saturn. The oldest of the gods should have a place, and the comparative immensity of the planet's orbit,

together with the fact that it was then the most remote planet from the sun, seemed in conformity with the god's age, and Uranus carried the day.

Herschel observed that the polar diameter of Uranus appeared shorter than the equatorial diameter, and since his time various observers have measured the difference. The ellipticity turns out to be about $\frac{1}{12}$. Uranus has four faint satellites—two discovered by Herschel and two by Lassell. The retrograde movements of the satellites was announced by Herschel in 1798 in the following terse language:—'I take this opportunity of announcing that the movement of the Georgian satellites is retrograde.' This was an unparalleled condition of motion, excepting comets, and was sufficient in itself to single out the planet as an object requiring especial research in order to investigate its genesis. Another fact which rendered the planet's system unique was the discovery by Herschel, in 1788, that the plane of the satellite's orbit was inclined 78° 58′ to the plane of the ecliptic. Young gives an inclination of 82° 2′. This plane contains the close, almost circular, orbits of all the four satellites which revolve round Uranus, being another deviation from the rule which would be deduced from the varied paths described by the obsequious attendants on the other planets. Observations that have as yet been made with a view to determine the time of rotation and the inclination of the Uranian axis have led to painfully discordant results. Buffham noticed some bright markings on Uranus in 1870-72, and from observations of their motions deduced the time of rotation as twelve hours, but the plane of rotation was *not* coincident with that of the satellites' orbit. Again, observations of dusky bands by Young in 1883, of apparent equatorial belts by the Brothers Henry in 1884, and Perrotin and Thollon's observations of a bright spot on the planet's disc in the same year, all support Buffham's conclusion and make the plane of rotation between 15° and 40° from the trend of the satellites. But observations of the bulging out of the planet's equator emphatically combat this statement. Schiaparelli, Young, Schafarik, observers of the ellipticity of Uranus, agree in saying that the plane of the planet's equator *is* that of the satellites' motion. If this be so, then there can be but one conclusion as to the plane in which the planet rotates, and therefore the inclination of the Uranian axis. The difference between these two sets of observations thus amounts to nearly half a right angle.

Herschel made the first observations of the mass of Uranus in 1788, and found it to be 17·140612 as compared with the earth, or about $\frac{1}{18000}$ that of the sun. Adams reduced all Herschel's observations of Uranian satellites, and obtained $\frac{1}{21165}$ as the planet's mass, whilst a reduction of Lassell's observations gave a value $\frac{1}{20897}$. Lamont, in 1837, from his own observations of the *orbits of the satellites, deduced a mass* $\frac{1}{24605}$. *Bouvard found, from perturbations of other planets,* $\frac{1}{17918}$; *whilst* Struve gave the fraction $\frac{1}{26860}$. The mass adopted by Newcomb is $\frac{1}{22600}$. This mass, revolving round the sun at a mean distance of about 1,800 millions of miles, must exert considerable influence upon bodies near it—an influence which may often predominate over that of the sun.

The volume of Uranus was found by Herschel to be 80·49256 greater than the earth's volume, whilst the density was less in the ratio of ·220401 to 1. Later observations have assigned Uranus a volume about 66 times that of the earth, hence the planet is about as much greater than the earth that the earth is greater than the moon.

The inclination of the orbit of Uranus to the ecliptic plane is the smallest of the planets, being only about 46′.

The spectrum of Uranus is quite different from the ordinary solar spectrum. In recent years, Messrs. Taylor and Fowler have measured the positions of the lines and bands in the spectrum, and the investigation has led to the conclusion that 'there can be very little doubt that Uranus is to a very large extent self-luminous, and that we do not see it wholly by reflected light.'

Neptune was known to be in existence before it was observed. Uranus does not move exactly in the path that it would if nothing disturbed its motion. It was suggested that the disturbing body was another planet outside Uranus. Calculations were made on this assumption in 1844-45 by Professor J. C. Adams in England and Le Verrier in France, and the position which ought to be occupied by the unknown planet predicted. Directed by Le Verrier, an observer named Dr. Galle pointed his telescope to a certain position in the sky, and in accordance with the prediction the unknown planet was found close to its calculated position. Neptune's mean distance from the sun is 2,800,000,000 miles, with a variation of 50,000,000, owing to the eccentricity of the orbit. The periodic time of the planet is 164 years, and the synodic period 367½ days. Its diameter is about 35,500 miles, its volume a little more than 90 times that of the earth, and its

mass about 18 times. Thus the density of the planet is $\frac{18}{90}$, or one-fifth that of the earth, or about the density of water. Neptune has one known satellite, about the same size as our own moon. It is very probable, however, that more satellites accompany the planet, but are too small to be visible on account of their enormous distance from us.

Since the death of Professor Adams, Professor Holden has published some notes concerning the discovery of Neptune. It is known that in October, 1845, Adams submitted to the then Astronomer Royal, Sir George Airy, his computations indicating the existence of an unknown world beyond Uranus. The work was shown to Dawes, and he was so much impressed by it that he wrote to Lassell, asking him to search for Neptune in the region designated by Adams. Had the discoverer of the two inner and

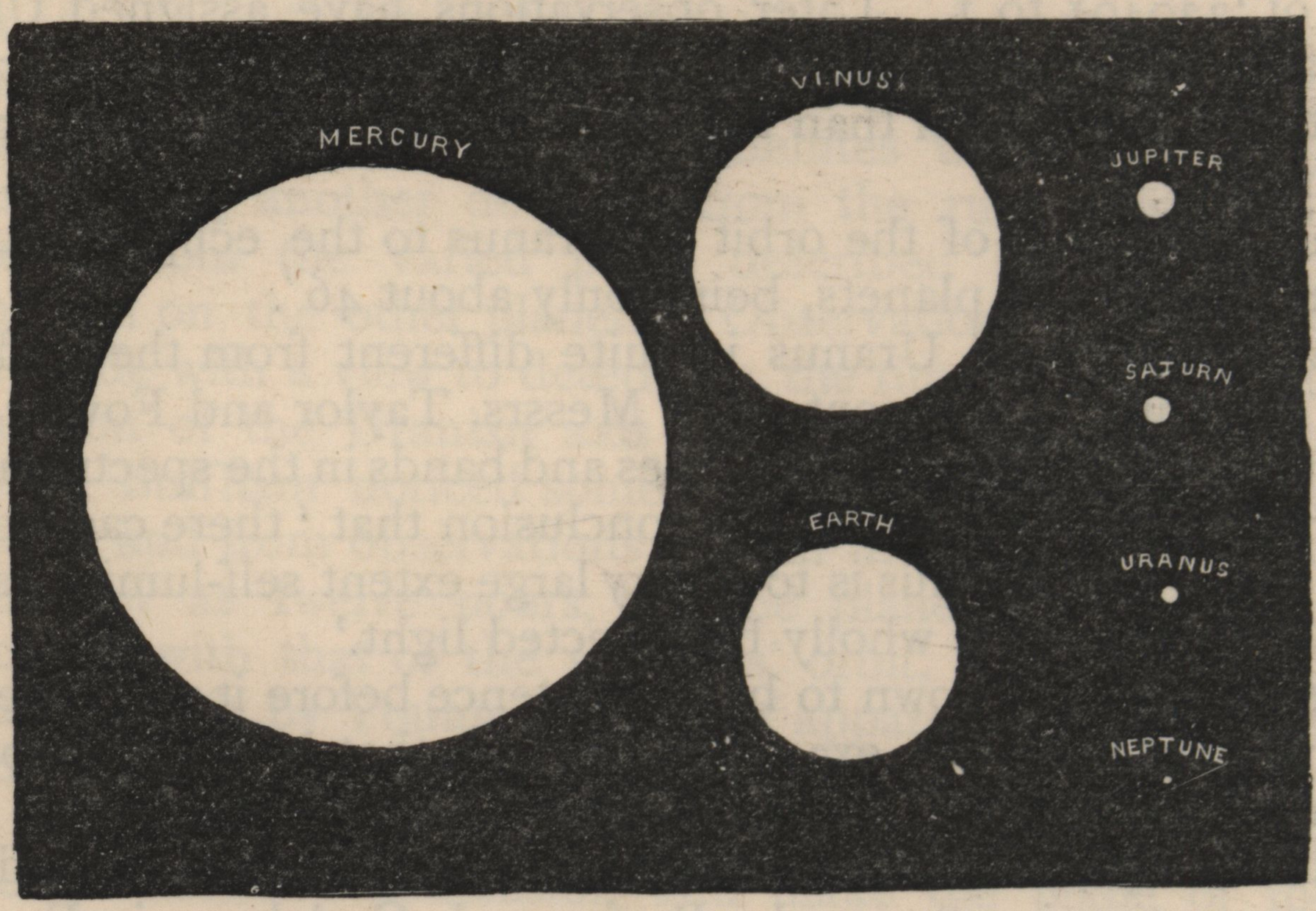


Fig. 88. Showing the apparent size of the Sun seen from the planets.

faint satellites of Uranus, and the satellite of Neptune, directed his instrument to this region, there is little doubt but that he would have seen the planet. However, the Fates ordained otherwise. Lassell was confined to his sofa by a sprained ankle, and when he recovered, the letter of Dawes, giving the predicted place of Neptune, could not be found. It turned out to have been destroyed by a too-zealous servant. Thus, 'by a set of curious chances,' the new planet was never looked for by the most skilful

observer with the then most powerful telescope in England. It was not until many months after the letter of Dawes to Lassell that the planet was found by Galle and D'Arrest near the position given by Le Verrier.

At the distance of Neptune, the sun would not appear such a mighty body as he does to us. As we have pointed out before, the apparent size of an object is inversely proportional to the distance. By applying this principle to the sun, we are able to calculate the apparent angular diameter of our luminary when viewed from all the planets. The results are shown in Fig. 88.

QUESTIONS ON CHAPTER IX.

1. Give an account of the appearances, observed in the telescope, on the surface of the planet Mars. (May, 1891.)

2. Describe the planet Saturn. (May, 1887.)

3. What are the views at present concerning the nature of Saturn's rings, and what are the facts on which these views are based? (May, 1881.)

4. State what you know about the planet Jupiter.

5. Explain the meaning of the word 'Planet,' write out a list of the planets in the order of their distances from the sun, and explain the term 'Transit of Venus.'

6. Describe the discovery of the planet Neptune.

7. Give a diagram showing the relative positions of the Earth, Venus, and the sun, when Venus is a 'morning,' and when she is an 'evening' star.

8. Describe the planet Mars.

9. Describe the facts which led to the discovery of the first asteroid.

10. How did Herschel discover Uranus, and how was he able to distinguish the planet from a star?

11. In what respect do the satellites of Uranus differ from other bodies of the same class?

CHAPTER X.

CELESTIAL CHEMISTRY.

Principles of Spectrum Analysis.—When a spectroscope is directed towards a flame in which a little common salt is burning, the observer will see a bright yellow line in the field of view. A good instrument will show this line double. If a small portion of a thallium salt be held in the flame, a green line appears. Strontium shows a number of red lines and a blue one, and barium a series of brilliant bands of red and green. Whenever these materials are burnt in this fashion, the lines particular to each substance are seen in the spectroscope. By utilising this fact, the spectroscopist is able to analyse a mixture without going through the tedious processes adopted by chemists. He burns the mixture in a flame and observes the flame by means of his spectroscope. Practice has made him familiar with the lines and bands which are the distinctive badges of different substances, so he names the substances in the mixture, one by one, as he observes the presence of their particular lines in the spectroscope. A Geissler tube enables us to extend this knowledge. Such a tube contains a gas of some kind, and the gas is rendered luminous by passing electricity through it. A gas so treated shows bright lines and bands similar to those given by the vapours of substances burnt in flame, but in different positions. And different gases exhibit different sets of lines, just as is the case with different solids turned into vapours by heat. If, however, the white hot lime cylinder of the calcium light is observed, a continuous ribbon of coloured light is seen extending from the darkest red to the darkest violet, and each colour merging beautifully into its neighbours. An incandescent ball of any other material shows the same continuous spectrum; so do gases when they are rendered luminous under pressure. Now suppose that

while the spectroscopist is analysing his mixture in the flame of his spirit lamp, a beam from a lime light is made to pass through the flame and impinge upon the slit plate of his instrument. The bright lines which he had been observing will then be seen as dark lines upon a continuous spectrum. But it is obvious that the mere passage of the beam through the flame cannot alter the luminosity of the substances burning in it. The only explanation, then, of the dark lines is that they only appear dark by contrast with the much brighter continuous spectrum of the lime light. That this is the true explanation is proved by shutting off the lime light. As soon as this is done, the lines due to the substances in the flame resume their bright appearance.

Kirchoff's Laws or Axioms.—The principles which we have illustrated experimentally are summed up in three laws or axioms enunciated by Kirchoff in 1860. These laws are stated as follows:—

(1.) Incandescent solid or liquid substances, and gases under pressure, give a continuous spectrum.

(2.) Vapours and gases under low pressure, when rendered luminous, give discontinuous spectra; that is, spectra consisting of a number of bright lines or bands, the positions of which are different for different substances.

(3.) Vapours and gases are opaque to those particular rays of light of which their own spectra consist.

Fraunhofer Lines.—It has been previously remarked that when the sun is observed spectroscopically, its spectrum is seen to be made up of numerous dark lines, known as Fraunhofer lines, from the name of the discoverer. The lines discovered by Fraunhofer are those easily seen with an ordinary spectroscope. They were denominated by him with letters of the alphabet, beginning with A and B in the red part of the spectrum, C in the scarlet, D in the yellow, E in the green, F and G in the blue, and H in the dark violet. The superior instruments now at our disposal have revealed hundreds of dark lines in addition to those seen by Fraunhofer, nevertheless, it is usual to call all of them Fraunhofer lines.

Solar Comparison Spectra.—If one-half of the slit of a spectroscope is illuminated by an image of the sun, and on the other half of its length light falls from an electric arc in which

iron is burning, two sets of spectra will be seen in the field of view of the spectroscope. The dark Fraunhofer lines will be seen in juxtaposition with bright lines due to iron vapour. Each line of iron has a corresponding line in the solar spectrum, and the coincidences will be found to be exact from the red to the violet end of the spectrum. Similar coincidences are found when Sodium, or Barium, or Calcium, or Hydrogen, are the substances used instead of iron for the comparison spectrum. Now, if only a few lines of a substance could be matched in this manner, the coincidence might, of course, be accidental, but when a thousand lines of iron occur in precisely the same positions as a thousand Fraunhofer lines, and the relative intensities of both are the same, it is impossible to deny that the Fraunhofer lines in question are manifestations of the existence of iron in the sun. The existence of other elements is similarly established when the lines in their spectra are matched by Fraunhofer lines. Professor Lockyer was one of the first investigators in this branch of solar physics. He not only observed the coincidences between Fraunhofer lines and the spectra of different elements, but photographed the two side by side. To do this one-half of the slit is first covered and the other half is illuminated by the light of the electric arc in which some substance is burning. A lens is employed to concentrate the light of the arc upon the slit. The half that has been open to the arc light is afterwards screened and the other half is exposed to sunlight. The solar spectrum thus falls upon the photographic plate and leaves its impressions. By this means two spectra are photographed under the same conditions, and when the plate is developed the lines of one will be above the other. Some of the lines in the pair of spectra will be coincident, others will not be so matched. If the substance burnt in the arc is pure, so that all the lines in its spectrum are really due to one particular substance and none are due to impurities, then wherever the coincidences occur the Fraunhofer line is said to represent in the sun the substance under examination.

Chemical Constitution of the Sun.—Professor Rowland, of Baltimore, has followed Professor Lockyer's method of photographing the spectrum of the sun with the spectra of different elements. He has done this for the spectra of all known elements, with the exception of a few gaseous ones, or those too rare to be yet obtained. The following table of solar elements has been constructed according to Professor Rowland's observa-

tions, though most of them have previously been given by other observers :—

Elements in the Sun, arranged according to the Number of Lines in the Solar Spectrum.

Iron (2,000 or more)	Magnesium (20 or more)
Nickel	Sodium (11)
Titanium	Silicon
Manganese	Strontium
Chromium	Barium
Cobalt	Aluminium (4)
Carbon (200 or more)	Cadmium
Vanadium	Rhodium
Zirconium	Erbium
Cerium	Zinc
Calcium (75 or more)	Copper (2)
Scandium	Silver (2)
Lanthanum	Glucinum (2)
Yttrium	Germanium
Niobium	Tin
Molybdenum	Lead (1)
Palladium	Potassium (1)

Doubtful Elements.

Iridium	Osmium	Platinum	Ruthenium
Tantalum	Thorium	Tungsten	Uranium

Not in the Solar Spectrum.

Antimony	Arsenic	Bismuth	Boron
Nitrogen	Caesium	Gold	Indium
Mercury	Phosphorus	Rubidium	Selenium
	Sulphur	Thallium	

With regard to these tables Professor Rowland says:—'The substances under the head of "Not in the Solar Spectrum" are often placed there because the elements have few strong lines or none at all in the limit of the solar spectrum, when the arc spectrum, which I have used, is employed. Some good reason generally appears for the absence of the lines of particular elements from the solar spectrum. Of course, there is little evidence of their absence from the sun itself; were the whole earth heated to the temperature of the sun, its spectrum would probably resemble that of the sun very closely.'

Explanation of Fraunhofer Lines.—From the illustrations of Kirchoff's laws which are given in the beginning of this chapter, the student will easily be able to comprehend why the lines in the solar spectrum are dark. The photospheric clouds are composed of solid or liquid particles, and if they existed without a surrounding atmosphere, the solar spectrum would be continuous. But the atmosphere contains the same substances in the form of vapour as have been condensed to clouds, that is to say, the light of the photospheric clouds has to pass through an atmosphere containing the same elements as exist in the clouds, before it can reach the earth. But each gaseous element blocks the way of a particular quality of light emitted by the photospheric clouds, and the result is a spectrum traversed by dark lines or gaps instead of the continuous spectrum that would have been seen had the gaseous atmosphere not existed. The atmosphere is analagous to the flame that was used in conjunction with the lime-light, and the lime-light itself plays the part of a photospheric cloud. When the lime-light is screened, the bright lines of the substances burning in the flame are visible. Similarly, when the light of the photosphere is shut off during an eclipse, the solar atmosphere is seen to give a spectrum of bright lines.

The Chromosphere.—Extending from the layer of gases and vapours in which the photospheric clouds float, to a height of from 5,000 to 10,000 miles, occurs a part of the sun's atmosphere known as the *chromosphere*. It is scarlet in colour, owing to the incandescence of the hydrogen of which it is mainly composed. The glare of the photosphere renders it impossible for the unaided eye to see the chromosphere except during a solar eclipse, but it can be studied by means of a spectroscope at any time when the sun is visible. The method of doing this was discovered independently by Professor Lockyer and Dr. Janssen in 1868. It consists in using a spectroscope of large dispersive power on a telescope. The light of the chromosphere consists chiefly of hydrogen light. Its spectrum is therefore a few bright lines, the most conspicuous being one in the scarlet part of the spectrum and one in the blue. The action of a high dispersion on these lines is simply to separate them. But the case is different with the continuous spectrum of sunlight, for as the high dispersion spreads out the spectrum its brightness is diminished, and the action can be carried so far that the chromosphere, and the prominences in it, can be seen by widening the slit of the spectroscope. Instead of seeing the prominences directly between

the jaws of a wide slit, an image of the sun is received on the slit plate of the spectroscope and arranged so that the slit is either tangential or radial to it. Suppose at first that the slit is radial to the limb. The dark lines of the solar spectrum will be seen in one part of the field, and at the ends of the hydrogen lines bright spikes will be visible. These spikes represent the height of that part of the chromosphere over which the slit is fixed. If the slit is carried round the sun's image radially, the height of the spikes will be found to vary as elevated and depressed regions of the chromospheric sea pass under it. By placing the slit tangentially to the limb, the extent of a prominence at any height can be found.

Chemistry of the Chromosphere and Prominences.—The chromosphere, and therefore the prominences, show all the lines of hydrogen and also lines of iron, magnesium, calcium, barium, and a number of other elements. But only a few of the lines of these elements are coincident with lines in the chromosphere spectrum, hence it is possible that such coincidences are accidental. Besides the known chromospheric elements, a line is always seen near the sodium lines in the yellow part of the spectrum. It is known as D_3 or the *Helium* line, and the element which gives rise to it is unknown in terrestrial chemistry.

Sun-spot Spectra.—If when the sun has spots upon it, the slit of a spectroscope is arranged across one of the spots, a dark line will be seen to cross the Fraunhofer lines in the field of view, producing somewhat the same effect as when a match is held across the slit. But a scrutiny of the spectrum shows that many of the Fraunhofer lines are thickened or widened where the sun-spot crosses them, whereas a match held across the slit simply produces a black line along the spectrum. Now the Fraunhofer lines are caused by absorption in the atmosphere of the sun, and since some of them are thickened at the sun-spot, it is evident that the absorbing effect is there increased. By observing the lines that are widened, the kind of vapour existing in a cool condition in the spot is found. Some observers record every widened line, but Professor Lockyer adopts the method of only recording the twelve lines most widened in each spot. These lines are found to differ at different parts of the sun-spot cycle, and observations have led to the conclusion that 'as we pass from minimum to maximum, the lines of the chemical elements gradually disappear from among those most widened, their places being taken by lines of which we

have at present no terrestrial representation.' The probable explanation of this is that when the sun is most active many of the chemical elements are decomposed into unknown substances.

Doppler's Principle.—If a musical instrument is emitting a note of constant pitch, and it and an observer are neither approaching nor receding from one another, a note of the same constant pitch as that given by the instrument is heard. But if the interval between the two is decreasing, the pitch is raised, while motion away from one another lowers the pitch. An illustration of this is afforded by the sound of a railway whistle. When the engine carrying the whistle and the listener are in relative rest, the pitch of the whistle has a certain value dependent upon the number of waves of sound sent out every second. If the engine is approaching the observer, the number of vibrations which reach the ear every second is increased, in other words, the pitch of the whistle is apparently raised. Motion away from the observer causes the number of vibrations which reach the ear in a second to be less, so the pitch of the whistle is lowered. An engine going at the rate of 40 miles per hour has the pitch of its whistle raised by a semitone when approaching a listener, and lowered by the same amount when receding. The principle holds good for light waves as well as for sound waves. The lines in a spectrum have a definite position in the light scale precisely analogous to the pitch of a note on the scale of sound. Motion towards an observer causes the light to be increased in pitch, that is, causes the lines to be shifted bodily towards the violet end of the spectrum, while a motion of recession causes a shift towards the opposite end. The amount of shift in each case depends upon the velocity of relative motion in the line joining the body sending out waves and the receiving station. The utilisation of this principle has led to many extremely interesting results. By means of it, the velocity with which hydrogen is shot out from the sun's chromosphere towards the earth is found, and movements of the vapours in sun-spots are estimated. And by applying the principle to the stars and nebulæ we are able to determine their motions 'in the line of sight.' More is said on this point in a later chapter.

Movements of Solar Vapours.—On some occasions, lines widened in the spectrum of a sunspot are considerably distorted, instead of appearing merely as images of the slit of the spectro-

scope. The distortion is produced by the approach or recession of the vapours which the lines in question represent. If, while a spot is under spectroscopic observation, a mass of hydrogen in it descend towards the sun's centre, the hydrogen lines will be shifted towards the red end of the spectrum, while the other lines are unaffected. The velocity generally varies in different parts of the spot, hence the hydrogen lines suffer different displacement in different parts of the spot-spectrum. On this account, the lines sometimes assume a zig-zag appearance. The distortion is not confined to hydrogen lines, but is exhibited by the lines of any vapour in motion towards or from the earth. In a similar manner, the movements of prominences are observed and measured, the bright spikes at the ends of prominence lines being altered by motion in the line of sight into irregular forms. The displacements observed in spot and prominence spectra often indicate a velocity so high as 250 miles per second.

Chemistry of Solar Corona.—The chief line seen in the spectrum of the corona is situated in the green. It was at first thought to be due to iron, but further observations have proved that this is not the case. No terrestrial element has been found to give a line which falls in exactly the same position as the characteristic line of the corona. Whatever the substance is, it is lighter than hydrogen—the lightest element known—for it exists at a much greater elevation than the hydrogen of the chromosphere. The name *coronium* has been given to the unknown element. In addition to the coronium line, lines of hydrogen are seen in the spectrum of the corona, and a large number of bright lines have been photographed. More lines are seen and photographed during a maximum than during a minimum of solar activity. A continuous spectrum is always given by the corona, and a few dark Fraunhofer lines are also seen. From these spectroscopic facts it appears probable that the corona consists of incandescent solid or liquid particles suspended in an extremely rare gaseous medium, the Fraunhofer lines being merely due to sunlight reflected by the particles.

Spectra of Stars.—Early spectroscopists found that stars gave spectra of dark lines, and, in many cases, spectra which were similar to the solar spectrum. By comparing the lines with those given by terrestrial elements, the chemical constitutions of stars have been determined. Hydrogen, iron, magnesium, sodium, calcium, and many other elements have thus been shown to enter

into the composition of stars. The spectra have been classified according to their appearance in the manner described in the following paragraph.

Classification of Stellar Spectra.—In 1823 Fraunhofer observed that some star spectra were similar to the solar spectrum and some dissimilar. Shortly afterwards, Rutherford, in America, arranged the spectra into three groups, as follows:—(1) Spectra containing a large number of lines and bands, like the solar spectrum; (2) Spectra containing a few broad lines; (3) Continuous spectra containing no lines at all. Secchi, an Italian astronomer, made a spectroscopic survey of the stars, and from the results of his observations, established four types of spectra, viz.:—Type I. White stars, in which dark and broad lines of hydrogen are the prominent feature. Type II. Yellow stars, with spectra almost indistinguishable from the solar spectrum. Type III. Deep-coloured stars, showing in their spectra dark and wide bands which fade away on their less refrangible sides, that is, on the sides nearer the red end of the spectrum. Type IV. Dark red stars, in which the bands fade away on their more refrangible sides. Vogel has arranged star spectra into three classes, each containing sub-classes. His classes are: (1) Spectra in which lines due to metals are very faint or invisible; (2) Spectra in which a large number of lines due to metals are conspicuous; (3.) Spectra in which the blue and red portions are faint and numerous dark bands occur in addition to lines due to metals. None of these classifications can be considered satisfactory, and Professor Lockyer has proposed a new grouping according to temperature, which is described in Chapter XII.

Spectra of Nebulæ.—It was found by Dr. Huggins in 1864 that nebulæ give spectra of bright lines. This was a very significant observation, for it showed that nebulæ were not distant clusters of stars, as had been previously supposed, but masses of luminous gas. In the visible spectrum four bright lines are conspicuous, though as many more have been seen by acute observers. A comparison of the nebular spectrum with luminous hydrogen shows that two of these lines are undoubtedly due to this element. The origins of the two remaining lines are doubtful. One of them, known as the 'chief nebular line,' from the fact that it is brighter than any of the others, was at first supposed to be due to nitrogen. The evidence for this conclusion lies in the circumstance that a double line of nitrogen falls in approximately the same position as

the nebular line. Professor Lockyer has suggested that the line in question has its origin in magnesium. His suggestion was the result of spectroscopic observations of meteorites. When meteoritic particles are placed in a tube devoid of air, and rendered luminous, a bright line is seen which appears to occupy precisely the same position as the nebular line. This line is due to magnesium. It fades away slightly on the violet edge, and the nebular line has been seen by some observers to present the same appearance. There is certainly a large amount of evidence in favour of the magnesium origin of the nebular line; but Professor Lockyer's idea has not yet been generally accepted. However, the suggestion has had one good result, for it has entirely done away with the idea that the line is due to nitrogen. Many nebulæ show a continuous spectrum instead of a spectrum of bright lines. As has already been stated, such a spectrum is produced either by an incandescent body or by gas under pressure. The probability is that nebulæ showing continuous spectra are in the latter condition. The photography of the spectra of nebulæ has revealed many new lines. On a photograph taken under Professor Lockyer's direction in 1890, twenty-eight lines occur, some of which appear to have their origins in magnesium, manganese, and carbon, while hydrogen lines are certainly present.

Bright-line Stars.—Some stars show spectra of bright lines in addition to dark bands, and very recently Professor Pickering of America has discovered a comparatively large number of stars which have spectra indistinguishable from that of a nebula. These are known to spectroscopists as 'bright-line stars.' Their existence indicates that the hard and fast distinction once supposed to divide stars from nebulæ, viz., that one group of celestial bodies gave dark, while the other gave bright lines, must be abandoned. In fact, spectroscopic observations indicate that there is a sequence between all kinds of spectra, that is to say, the nebular spectrum merges into star spectra, and all types of star spectra merge into one another. The great difficulty is to establish the order in which the different spectra follow each other.

Spectra of Comets.—In general, the spectrum of a comet is the same as that given by the blue base of an ordinary candle flame, and therefore has its origin in hydrocarbons. The nucleus of a comet gives a continuous spectrum, and the bands of hydrocarbon are seen upon it. These observations are sufficient to

show that comets are self-luminous bodies, and not bodies merely reflecting the light of the sun, though, to a small extent, of course, this must be the case. In fact, Fraunhofer lines due to reflected sunlight have been observed in cometary spectra. We have said that the spectrum of a comet is generally that of a hydrocarbon, but there are several exceptions to this. A couple of comets have been observed which exhibited in their spectra the characteristic line of a nebula, and some cometary spectra are recorded as consisting of bright lines of iron, magnesium, and sodium without a trace of the hydrocarbon bands.

The Spectrum of the Aurora.—About sixteen bright lines have been observed in the spectrum of the aurora borealis. These have their probable origin in magnesium, manganese, lead, carbon, and iron. It is known that aurora displays are caused by electric discharges in the higher regions of our atmosphere. There is also every reason to believe that these regions contain a large number of meteoritic particles; and the probability is that the bright lines exhibited by the auroral spectrum are produced by the vapourisation of the constituents of these particles.

The Spectrum of the Zodiacal Light.—In the spring and autumn a faint luminosity can be seen to extend along the ecliptic from the sun. This is the zodiacal light, but very little is known as to the cause which produces it. It is an enormous ring of some kind of matter surrounding the sun in a similar manner to the rings surrounding the planet Saturn, and probably connected with the solar corona. The general opinion is that the light is produced by a large number of solid particles reflecting the light of the sun, but there is evidence that this is not the case. In many respects, the zodiacal light is similar to the aurora. More auroræ are observed in the spring and autumn, and at those times the zodiacal light is best visible. Though the spectrum of the latter is often said to be purely continuous, several reliable observers have seen in it the characteristic line of the aurora.

Spectra of Meteors.—Meteors are such transient phenomena that very few observations have been made of their spectra. Among the bright lines which have been detected are some having their origin in sodium, magnesium, iron, and carbon.

QUESTIONS ON CHAPTER X.

1. Compare the chemical constitution of the crust of the earth with that of the atmosphere of the sun. (May, 1884.)

2. Compare the chemical constitution of the crust of the earth with that of the sun's atmosphere, comets, and nebulæ. (May, 1878.)

3. In what way does the spectroscope enable us to determine the composition of the heavenly bodies? (May, 1883.)

4. State what you know concerning the chemical and physical constitution of stars, excluding the sun. (May, 1882.)

5. How do you account for the dark lines in the solar spectrum? (May, 1885.)

6. How has the chemical composition of the solar atmosphere been determined, and how can we measure the velocity with which the various vapours move in that atmosphere? (May, 1877.)

7. Why does the spectroscope enable us to view the solar prominences without an eclipse? (December, 1889.)

8. State the chief chemical elements in the earth's crust and atmosphere and the chief elements in the atmosphere of the sun. (December, 1887.)

9. What has the spectroscope taught us concerning the chemical and physical constitution of the atmosphere of the sun? (December, 1881.)

10. State what you know about the composition of white light, and show (1) how this may be studied by simple experiments, and (2) its bearing upon the composition of stars. (December, 1879.)

CHAPTER XI.

COMETS AND METEORITES.

Comets.—On rare occasions bright filmy bodies of irregular forms appear in the sky, and move through constellations like planets. Unlike the steady-going members of our family, however, they do not keep near the ecliptic, but travel along any part of the sky. These bodies are called comets, and their erratic motions, varying forms, great size and conspicuous brilliancy have always attracted attention. 'Shaking their horrid hair—causing pestilence—predicting wars—threatening the earth, now with fire, now with flood—these harmless wanderers have been especially cherished by the superstitious principle in man; nor was it until very recent years that they exchanged their fancied demoniacal mission into that of ambassadors from the farthest spaces of our firmament, where their home and relations are found.'

Number and Naming of Comets.—Though few comets appear which are well visible to the naked eye, a comparatively large number of telescopic comets are seen. On the average, about six comets are seen in telescopes every year, and many more must appear in the sky and be overlooked. A comet is usually named after its discoverer, thus, we have Donati's comet, which appeared in 1858, and Coggia's comet. Another method of distinguishing one comet from another is to use the letters of the alphabet to denote the order of discovery in any year, thus, comet *a*, 1893, is affixed to the first comet discovered in 1893; comet *b*, 1893, distinguishes the second, and so on through the year. The order of perihelion passage is also frequently adopted, Roman numerals being used in this case, thus, comet I., 1893, distinguishes the comet which passes its perihelion point first in 1893. On account of these different systems of nomenclature, comets frequently have several aliases.

Appearances of Comets.—Comets bright enough to be seen with the naked eye appear to be made up of a bright part called the *head* or *coma*, and a more hazy appendage termed the

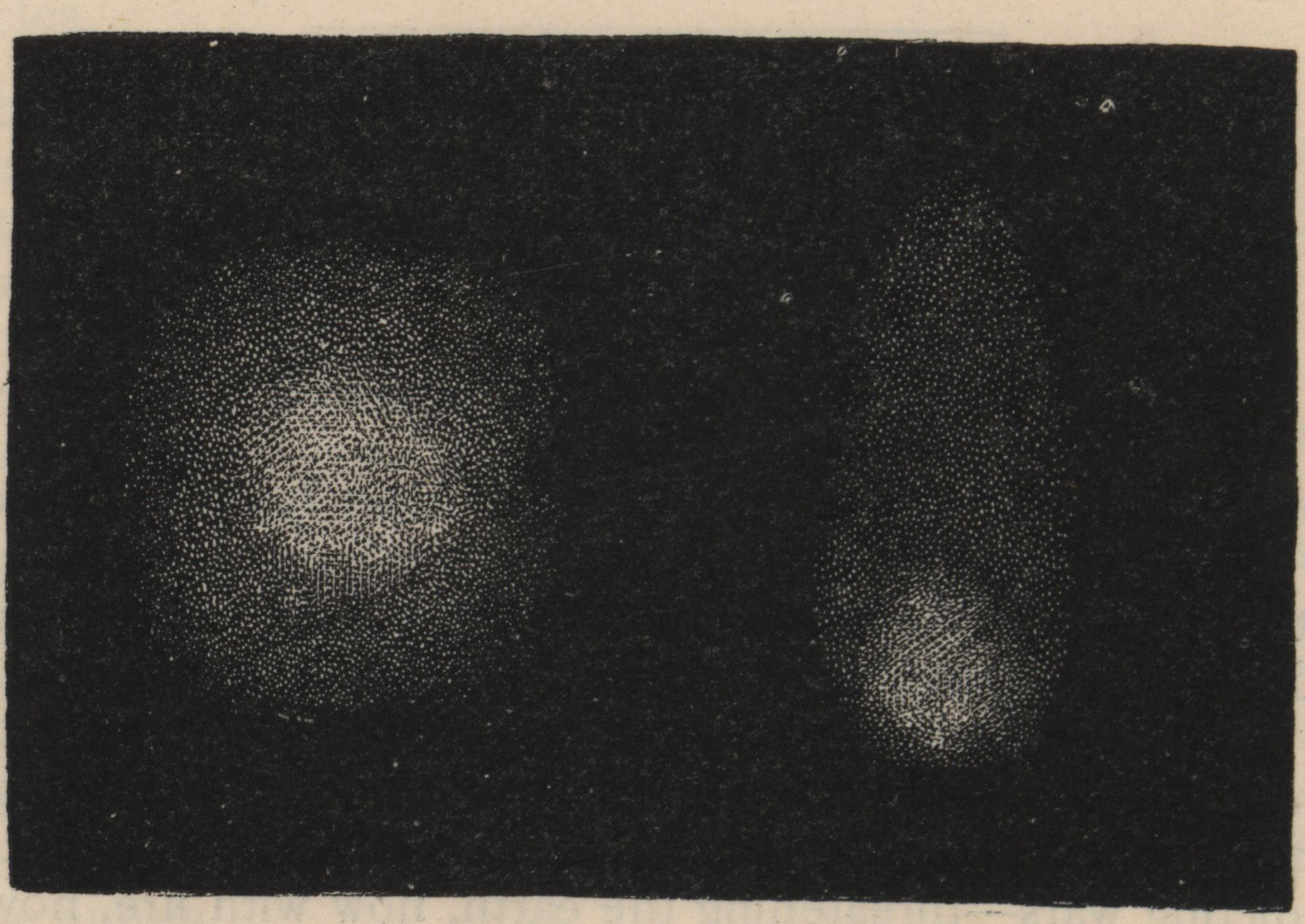


Fig. 89. Views of Telescopic Comets.

tail. Near the centre of the head a brighter *nucleus* is often visible. Telescopic comets generally have the appearance of patches of mist without any tail or nucleus, and this is especially

the case when the object is at a considerable distance from the sun. (Fig. 89.) In journeying round the sun, remarkable changes frequently occur. A nucleus is first developed. From it *jets* of luminous matter are shot out towards the sun, and are then turned back as if our luminary had a repellent action upon the material of which they are composed. As the comet increases in brightness, a series of more or less concentric *envelopes* surround the nucleus on the side near the sun, and



Fig. 90. Showing the nucleus and envelopes of the Comet of 1858.

bend back to form the tail or tails. (Fig. 90.) The action increases in violence until a few days after the comet has passed its perihelion point, when a diminution of brilliancy sets in. The tail, being composed of the vapours driven off in jets, is repelled by the sun, consequently it is always directed away from the sun, sometimes preceding and sometimes following the head. (Fig. 91.) These are the changes which generally occur. In a few cases, however, comets decrease in size as they approach the sun and increase as they recede from it.

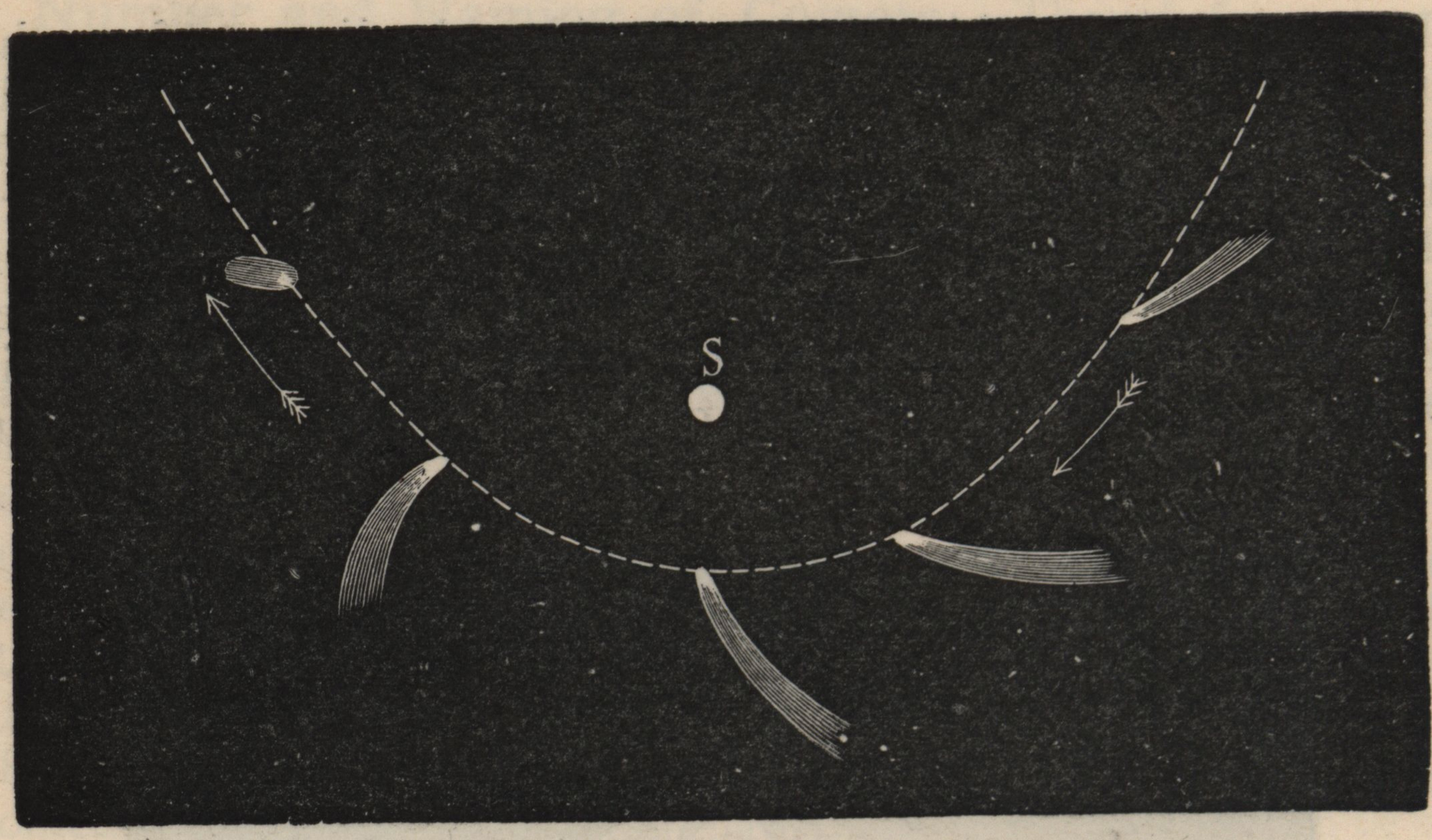


Fig. 91. Showing the direction of a Comet's tail with respect to the Sun.

Sizes of Comets.—From what has been said, it is evident that the dimensions of comets are constantly changing. The heads vary in diameter from about 10,000 to 50,000 miles, but in a few cases this has been considerably exceeded. A comet which appeared in 1811 had a head 1,250,000 miles in diameter for a short time, and Donati's comet of 1858 measured 250,000 miles across the head. The tails of naked-eye comets vary from about 5,000,000 to 50,000,000 miles in length, and the comet of 1843 had a tail fully 110,000,000 miles long. When these numbers are considered, the bulk or volume of a large comet is seen to be enormous.

Masses of Comets.—Though comets are so large in size, their masses are extremely small. This is evidenced by the fact that members of our system are not disturbed in the slightest by the movement of a comet near them. The effect of such an approach is to cause the comet itself to change its path. Our little earth has passed through the tail of a comet without the minutest alteration occurring in the length of the year, and comets have grazed against the satellites of Jupiter without causing any change in their motions.

The Density of Comets.—Since the volume of a comet is large and the mass is very small, the density of the object, as a whole, must be small. The fact that stars are seen through

comets without suffering any displacement also testifies to the extreme tenuity of these bodies. It has been calculated that an immense comet's tail compressed until it had a density equal to that of our atmosphere at sea-level, would not occupy more than a cubic inch, hence the tail is a far better vacuum than any we can produce by artificial means. There is very little doubt that the head of a comet is a swarm of meteorites, and the density of individual meteorites is, of course, much higher than that of the tail; but when the total mass is divided by the total volume, the resulting density of the lot is very small indeed.

The Tails of Comets.—A comet is very probably nothing but a swarm of solid particles or meteorites revolving round the sun, and its tail consists of the vapours of the substances contained



Fig. 92. View of the Great Comet of 1858, showing the plumy tail.

in the meteorites forming the swarm. Hence the amount of vapour increases as a comet approaches the sun on account of the increase of temperature due to more frequent collisions of individual meteorites forming the swarm, and therefore the tail of the comet increases in size. This almost invariably happens. A comet which appeared in 1874 showed a remarkable increase in the length of its tail as it approached the sun. In 16 days the tail grew from 4,000,000 to 25,000,000 miles in length. As the vapours are formed, they are driven away from the comet's head by the repellent energy of the sun, this repelling force being probably due to electricity. Some of the vapours driven off are more strongly repelled than others, and the shape of a comet's tail depends to a certain extent upon this fact. When the vapours are formed, two forces act upon them:—(1) The gravitational stress pulls them towards the sun, (2) an unknown stress tends to drive them away. Hydrogen is the lightest gas, and at the same time is most strongly influenced by the repelling action. Hence when it is driven off, the repellent action predominates. When the vapours emitted are heavy, and at the same time not strongly repelled from the sun, they form short and curved tails instead of long and straight.

Professor Bredichin, of Moscow, has classified the tails of comets according to their shape, and has calculated the ratio which gravitational attraction bears to the repellent action in the case of each. His results are as follows:—

(1.) Straight or hydrogen tails.—The repelling force is about 12 times greater than the attraction due to gravitation. Particles of vapour leave the nucleus with a velocity of about 15,000 feet per second.

(2.) Plumy or curved tails.—The repellent and attractive forces are nearly equal. Velocity of particles leaving nucleus, about 3,000 feet per second.

(3.) Short, strongly bent, or iron tails.—Gravitational attraction five times greater than repellent action. Velocity of particles shot out from nucleus, about 1,000 feet per second.

As comets recede from the sun, the tails usually decrease in size, and when a comet is at aphelion—when it is as far as it can go from the sun—it then presents the appearance of a hazy disc quite indistinguishable from a nebula.

Meteorites.—A shooting star is a particle of matter which has been attracted into the earth's atmosphere and rendered luminous by the friction put upon it. Sometimes very bright balls of light are seen to pass through the air like shooting-stars. These are known as meteors or fireballs. It is probable that meteors are large shooting-stars, but this has been doubted. Occasionally the heat developed by friction against the earth's atmosphere is not sufficient to entirely vapourize the whole fragment of matter, and a portion falls to the ground as a *meteorite*, the fall being usually accompanied by an explosion.

The Substances in Meteorites.—Most of the meteorites which have been found are of a *stony* nature; these are termed *aerolites*, and their chief constituent is olivine or peridote. A few, consisting almost entirely of iron associated with nickel, are termed *siderites* or meteoric irons. The former more closely resemble the constitution of the earth's crust than the latter. Varieties intermediate between these two are termed siderolites. The minerals found in aerolites and siderites respectively, and the elements which form them, are shown below. Some of the minerals, *e.g.*, augite and olivine, are abundant on the earth, while others, *e.g.*, schreibersite, are only found in meteorites. Though quartz is so abundant on the earth, it is not found in meteorites.

AEROLITES.

Mineral.	Elements in Mineral.
Olivine ...	Magnesium, Iron, Oxygen, Silicon.
Enstatite ...	Magnesium, Oxygen, Silicon.
Bronzite ...	Magnesium, Iron, Oxygen, Silicon.
Troilite ...	Iron, Sulphur.
Chromite...	Iron, Oxygen, Chromium, Aluminium, Magnesium.
Anorthite....	Calcium, Aluminium, Silicon, Oxygen.
Augite ...	Silicon, Oxygen, Calcium, Magnesium, Manganese, Iron.

In addition to these, aerolites contain nickel-iron, silicates of calcium, sodium and magnesium, carbon in combination with hydrogen and oxygen, and sulphates of magnesium, calcium, sodium, and potassium. It must not be supposed, however, that every aerolite contains these substances.

Siderites.

Mineral.	Elements in Mineral.
Nickel-iron	Iron, Nickel, Copper, Manganese.
Troilite	Iron, Sulphur.
Graphite	Carbon.
Schreibersite	Iron, Nickel, Phosphorus.
Daubreelite	Iron, Chromium, Sulphur.

The Elements in Meteorites.—From the tables showing the general constitution of siderolites and siderites, it will be seen that the elements most frequently found in these bodies are as follows:—

Metals.		Non-metals.
Iron.	Sodium.	Oxygen.
Magnesium.	Lead.	Hydrogen.
Manganese.	Lithium.	Carbon.
Nickel.	Strontium.	Sulphur.
Calcium.	Titanium.	Phosphorus.
Chromium.	Cobalt.	Silicon.
Copper.	Arsenic.	Nitrogen.
Aluminium.	Antimony.	Chlorine.
Potassium.	Tin.	

About twenty-six elements in all have been found in meteorites. Carbon has been found in the form of diamond, but this is rather rare. Hydrogen is occluded in meteorites, that is, it is enclosed between the solid particles. When a fragment of a meteorite is heated, the first result is the driving out of the hydrogen and other occluded substances. Microscopical examination of sections of meteorites shows the existence of oval or rounded particles termed *chondroids*, which were either rounded by friction with other particles, or condensed out of vapour into a more or less globular form. The outside of a meteorite has a glassy appearance, due to the fusion of the surface in passing through the air. In it are usually a number of depressions or pittings, known as *thumb-marks*, which have every appearance of marks produced by the collision of solid particles against a softer material, though possibly they are formed by the melting and vaporisation of materials softer than the remainder of the mass.

Number of Meteorites.—The number of meteorites which have been observed to fall is about three hundred, but the number which enter the earth's atmosphere as shooting stars is

countless. It has been found that on the average the number of luminous meteors seen between 12 and 1 on a clear night is fourteen. Six times this number would represent the number which would be seen if the observer could watch the whole of the atmosphere above his horizon, and it has been calculated that, 'making all proper corrections, the number which might be visible over the whole earth would be a little greater than 10,000 times as many as could be seen at one place. From this we gather that not less than twenty millions of luminous meteors fall upon our planet daily, each of which on a dark clear night would present us with the well-known phenomenon of a shooting star.

'This number, however, by no means represents the total number of minute meteorites that enter our atmosphere, because many entirely invisible to the naked eye are often seen in telescopes. It has been suggested that the number of meteorites, if these were included, would be increased at least twenty-fold; this would give us 400 millions of meteorites falling on the earth's surface daily. If we consider, however, only those visible to the naked eye, and if we assume that the absolute velocity of the meteors in space is equal to that of comets moving in parabolic orbits, Professor H. A. Newton has shown that the average number of meteorites in the space that the earth traverses is in each volume equal to the earth about 30,000. This gives us a result in round numbers that the meteorites are distributed each 250 miles from its neighbours. If, then, these observations may be accepted to be good for any part of space, we may, and indeed must, expect celestial phenomena which can be traced to meteorites in all parts of space.' *

Collisions of Meteorites. — The velocity of luminous meteors varies from ten to fifty miles per second, and the average is taken to be about thirty miles per second. The result of the collision of two bodies having these velocities is a very great increase of temperature. Prof. Lockyer has considered the effects of collision. In his words, 'The question of what must happen to the meteorites themselves in consequence of this system of collisions is worth going into thoroughly. A very cursory examination seems to indicate that much light is thrown on the condition of meteorites as we know them and their division into iron and stones.

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* Lockyer's 'Researches on Meteorites, 1887.'

'As 30 miles per second is a very frequent value obtained for the velocity of meteorites when they enter our atmosphere, it is possible to compare temperatures brought about by collisions with those produced by passage through our atmosphere. Two masses of meteoric iron meeting each other in space would probably, if moving with a certain velocity, be formed into a pasty, conjoined mass, and this process might go on until an iron of large dimensions was formed, and the various meteorites thus welded together would present in time a very fragmentary appearance. While irons were thus increasing in size, collisions with smaller meteorites would be attended with very local increases of temperature, perhaps sufficient to volatilise the surface or allow it to be indented, and in this manner the well-known "thumb-marks" receive explanation.

'The masses of iron, when in a state of fusion, whatever their size, would be able to include stony meteorites in their vicinity. In the case of stones it is easy to see that the result would be very different. Their collisions would have, most probably, the effect of reducing large pre-existing masses to smaller ones, and the collision of a large stone with a large iron would probably effect the driving of the stone into fragments, while the iron would be liquefied so as to enclose some of the fragments in its mass.'

Identity of Comets and Meteorites.—In 1857, Reichenbach, from the consideration of the structure of meteorites, and the facts then known with regard to comets, came to the following conclusions:—

(1.) That a comet's tail must consist of a swarm of extremely small but solid particles or granules.

(2.) That every granule is far away from its neighbour; in fact, so far that a ray of light has an uninterrupted course through the swarm.

(3.) That these granules, suspended in space, move freely and yield to outer and inner agencies, agglomerate, condense or expand; that a comet's nucleus, where one is present, is nothing else than such an agglomeration of loose substances consisting of particles.

Newton and Schiaparelli, in 1866, identified two comets with two swarms of meteorites, which, it was suggested, had been drawn into our system by the attraction of the sun and planets. This idea was supported by later researches, and Prof. Lockyer

showed, in 1889, that the changes in the spectrum of a comet during its revolution round the sun were precisely those which result from heating meteorites to different temperatures.

Showers of Shooting Stars.—Occasionally shooting stars appear in the sky in thousands; indeed, they have been observed in such vast numbers as to be comparable to the flakes of snow which fall during a snow-storm. In the day such showers of meteors give the sky a peculiar mottled appearance. A very noticeable feature during a meteoric shower is that all the meteors seem to shoot out or radiate from a particular part of the sky, known as the *radiant*, or *radiant point*. This is merely an effect of perspective. All the meteoritic particles travel in paths practically parallel to one another, and the radiant has been well termed the vanishing point of these paths. These radiants appear in various constellations, and it is usual to name meteors which radiate from the radiant point in the constellation Leo, Leonids, those which diverge from the Andromeda radiant are Andromedes, and the meteors of Perseus are Perseids.

Periodicity of Meteoric Showers.—In the early part of August in every year a shower of shooting stars occurs, the radiant point of which is in the constellation Perseus. The part of the earth's orbit occupied by the earth in the beginning of August must therefore be filled with more than the average quantity of meteoritic particles. There is evidence to show that the particles which give rise to the August shower are part of a ring of similar bodies surrounding the sun and in motion round it. The ring cuts the earth's orbit at the point in which the earth is during August, and, when we are passing through it, showers of shooting stars take place. An examination of old records by Professor Newton shows that showers of shooting stars have been seen about the middle of November every thirty-three years, the radiant being in the constellation Leo. He traced the showers back to 902 A.D., taking into account, of course, the changes in the calendar. Now, if we are dealing with a ring of meteoritic particles crossing the earth's orbit, a shower must occur every year. It is evident, therefore, that the November meteors are not part of a ring, and investigations show that they are part of a more or less concentrated swarm of meteorites moving round the sun in a long ellipse like a flock of birds. The orbit of the swarm cuts the earth's orbit at the point occupied by the earth about

November 14; but it is only when the earth and the swarm reach this point together, that is, every thirty-three years, that a brilliant shower takes place. The shower is much more brilliant than those recurring at a certain time each year, because the meteorites which produce it are not so scattered along their orbits. In 1866, a splendid display was observed, and the next will occur in 1899. The meteors which diverge from a point in Andromeda at the end of November are known as Bielids, for a reason to be explained later. The period of this group is thirteen years.

Connection between Comets and Meteors.—In 1866 the orbit of a comet—known as Tempel's—was found to be nearly identical with that of the November swarm of meteorites. A little later the meteors that appear in August were found to move in an orbit having nearly the same elements as a comet which appeared in 1862. The connection in one of these cases will be seen from the following comparison of elements :—

Elements of Orbits.	Meteoritic Orbit.	Orbit of Tempel's Comet.
Perihelion Distance	0·9893 ...	0·9765
Eccentricity	0·9033 ...	0·9054
Semi-axis Major	10·340 ...	10·324
Inclination	18° 3′ ...	17° 8′
Longitude of Ascending Node	51° 28′ ...	51° 26′
Period in years	33·25 ...	33·17
Direction of Motion ..	... Retrograde ...	Retrograde.

About half a dozen similar coincidences of cometary with meteoritic orbits are now known, and serve to establish the identity between the two groups of bodies. Evidence of this connection is also afforded by the analysis of the lights of comets and meteorites. From this evidence it is now believed that all comets are swarms of meteorites, though it is not known whether they are the thickest part of the swarm or not. 'The innumerable meteors which form the November swarm are arranged in an enormous stream of a breadth very small in comparison with its length. If we represent the orbit by an ellipse whose length is seven feet, then the meteor stream will be represented by a thread of the finest sewing silk, about a foot and a half or two feet long, creeping along the orbit.' The position which Tempel's comet occupies in this stream is doubtful.

Origin of Comets.—It is now generally believed that comets having parabolic orbits have been drawn into our system from outer space by the attraction of the sun and one of the larger planets. This is supported by the fact that the orbits do not lie near the ecliptic, like the orbits of planets and satellites. If a comet, moving in a parabolic orbit, has its velocity increased by passing near a planet, the parabola is transformed into a hyperbola, and the comet leaves the solar system, never to return again; if the velocity is decreased, the parabola is changed to an ellipse, and the comet becomes periodic. In this case the comet must return, after a time, to the point where the disturbance occurred. It is found that the seventeen comets having periods from three to nine years pass very near to the point occupied by Jupiter at aphelion. This unequal distribution along the ecliptic cannot be accidental, and is in favour of the capture of comets by Jupiter. The other major planets also have 'comet families' of their own. Le Verrier has shown that Tempel's comet, that is, the November swarm of meteorites, passed very near to the position occupied by Uranus in 120 A.D., and a natural conclusion from this is that the comet was captured by Uranus at that time.

If, during an eruption, matter were ejected from a planet with sufficient velocity, it would leave the planet altogether, and describe an orbit similar to the orbit of a short-period comet. The ejected matter would return after a time to the point where the explosion occurred. Relying on these facts, it has been suggested that periodic comets were ejected from the sun and planets instead of being captured from outer space; but this theory is not now accepted, and some recent investigations by Professor Newton and others have entirely disproved it. Professor Newton has established the following propositions relative to the perturbations by planets which lead to the annexation of comets:—

(1.) If a comet passes in front of Jupiter, the kinetic energy of the comet is diminished; if it passes behind the planet, the kinetic energy of the comet is increased.

(2.) The greatest effect of perturbation of a planet moving in a circular orbit in shortening the periodic time of a comet originally moving in a parabola, is obtained if the comet's original orbit actually intersects the planet's orbit at an angle of 45°, and if the comet is due first at the point of intersection at the instant when the planet's distance

therefrom is equal to the planet's distance from the sun multiplied by the ratio of the mass of the planet to the mass of the sun.

(3.) If in a given period of time 1,000,000,000 comets come in parabolic orbits nearer to the sun than Jupiter, 126 of them will have their orbits changed into ellipses with periodic times less than one-half that of Jupiter; 839 of them will have their orbits changed into ellipses with periodic times less than that of Jupiter; 1,701 of them will have their orbits changed into ellipses with periodic times less than one and a half times that of Jupiter; and 2,670 of them will have their orbits changed into ellipses with periodic times less than twice that of Jupiter.

(4.) Of the 839 comets which are reduced to have periodic times less than Jupiter's period, 200 will, after perturbation, have retrograde motions, and 639 will have direct motions.

(5.) Somewhat more than five times as many of these comets move in direct orbits inclined less than 30° to Jupiter's orbit as move in retrograde orbits inclined less than 30° to Jupiter's orbit. It may therefore be said that comets which are changed by the perturbing action of a planet from parabolic orbits of every possible inclination to the ecliptic into short period ellipses must, as a rule, move in orbits of moderate inclination, and with direct motions.

The Temperature of a Swarm of Meteorites.—Three chief causes determine the temperature of a swarm of meteorites in our system, and therefore of a comet. They are (1) the distance of the meteorites from the sun; (2) number of meteorites scattered along the orbit; (3) the velocity of meteorites round the common centre of gravity. The methods adopted by Prof. Lockyer for studying the spectra of meteorites at different temperatures and in vacuo have been described. There is no reason to believe that a meteorite or many meteorites, subjected to varying temperatures in space, would behave different from those in the laboratory. If a comet is a swarm of meteorites, it is coolest when at aphelion and increases in temperature as the sun is approached, and the variation should have roughly the same sequence as that found in laboratory experiments. For it must

be at once understood that a comet does not increase in brilliancy merely because of proximity to the sun, but because a greater tidal action is set up in the meteoritic swarm. As the sun is approached, the individual meteorites move faster, and accordingly meet one another oftener. The result of this increase of collisions is to raise the temperature of the meteorites and so to render them more and more luminous.

The Spectra of Meteorites.—Professor Lockyer has examined the light given out by meteorites at different temperatures. Fragments of a meteorite are placed in a tube, and the air is exhausted by means of an air-pump. The tube has two platinum wires let into it which are connected with an induction coil, hence it is practically the same as a Geissler tube containing meteoritic fragments. When the coil is put in action, an electric glow passes over the fragments. Viewed in the spectroscope the first lines which show themselves are due to hydrogen. Carbon also exhibits its presence. Both these substances are generally occluded in the meteorite, and easily driven out. If the tube is then slightly warmed by placing a Bunsen flame under it, a bright line due to magnesium appears in the green part of the spectrum, and another slightly nearer the violet end. These two lines appear to occupy the same positions as two lines in the nebular spectrum, though the coincidence is doubted by many spectroscopists. On further heating the tube containing the meteoritic fragments, other magnesium lines appear, carbon flutings or bands become more visible, and a large number of other elements manifest themselves. At the temperature of the oxy-hydrogen flame, about a dozen lines are seen and identified with magnesium, iron, sodium, lithium, potassium, and manganese, while at the higher temperature of the electric spark, strontium, barium, calcium, chromium, zinc, bismuth, and nickel are added.

Low Temperature Spectra.—The light emitted by most substances varies in quality at different temperatures. Thus, the spectrum of iron at the temperature of the oxy-hydrogen flame is vastly different from the spectrum of iron burnt in the electric arc. When an iron meteorite is burnt in the electric arc, and the solar spectrum is observed or photographed in juxtaposition with its spectrum, all the bright lines due to substances in the meteorite coincide with dark lines in the sun. Professor

Lockyer's conclusions from observations of the spectra of meteorites can be stated as follows :—

(1.) Low temperature lines of magnesium, sodium, iron, chromium, manganese, strontium, calcium, barium, potassium, zinc, bismuth, and nickel are seen in meteorites subjected to such temperatures as the Bunsen burner and oxy-hydrogen flame.

(2.) The line of magnesium most frequently seen is the remnant of a fluting. This line is brightest at the lowest temperature, its brightness decreasing as the temperature is increased.

(3.) The only line of manganese visible at the temperature of the Bunsen burner is the one exhibited by meteorites.

(4.) The lines of iron seen in the spectra of meteorites are those which are brightest at the temperature of the oxy-hydrogen flame.

Changes in the Cometary Spectrum.—In a couple of comets at a considerable distance from the sun, Dr. Huggins has observed the chief nebular line—the line which, according to Professor Lockyer, is one of the first seen when a meteorite is heated. This is the brightest line of magnesium at a low temperature. As comets increase in temperature, the light from comparatively cool carbon vapours manifests itself, and then the light from hot carbon replaces it. After this stage, light due to manganese or lead is radiated, and then it is absorbed, the result being that we get effects due to manganese and lead absorption. The highest temperature is reached when lines of iron are seen in the spectrum. This only happens when a comet approaches very near to the sun. As a comet recedes from the sun, a similar series of changes occurs in the reverse order. This sequence has never been completed by one comet. Most comets are not observed beyond the hot carbon stage, and so neither cool carbon nor magnesium are seen in them. Some never get hot enough to complete the sequence, while some are not seen cold enough to complete it. After a detailed investigation of all cometary spectra, Professor Lockyer has been able to construct the sequence stated above. What was wanting in some comets was found in others, and link by link the chain of evidence has been put together in support of the idea that comets and meteorites are one and the same phenomenon.

Spectra of Certain Comets.—All comets show the existence of carbon at some time or other during their journey round the sun, and the spectroscope can discriminate between carbon at a high temperature and carbon which is not so hot. Hence, cool carbon must be seen when a comet is further from the sun than when hot carbon is seen. This was what was observed in Winnecke's comet in 1877, and in Brorsen's comet in 1879. It is at the hot carbon stage that comets are generally observed; indeed, the three bands of light due to hot carbon have so often been seen in cometary spectra as to earn for themselves the name of 'cometary bands.' The great comet of 1882 is a good example of the changes which occur in comets when they are near the sun. It approached to within 300,000 miles from the sun's surface; that is, the distance from the centre of the sun to the perihelion point was about 700,000 miles. This was remarkable, as the first comet which appeared in 1882, Well's comet, only approached to a little more than 5,000,000 miles from the sun, while Tuttle's comet was 96,000,000 miles distant from the sun at its nearest approach. The spectroscope was used to analyse the light of the great comet of 1882 a day after perihelion. Bright iron lines were then seen. Eleven days later, when the comet was rushing away from the sun, the light from a bright band due to iron was observed, and indicated a decrease of temperature. Thirty-four days after perihelion these phenomena had disappeared, and radiation, due to manganese, was seen; and forty-two days after perihelion only the three comet bands indicative of hot carbon could be detected. If the comet could have been pursued into space, we should doubtless have seen hot carbon replaced by cool carbon; and, last of all, when it was at its lowest temperature, only the low-temperature line of magnesium would have been left.

Some observations of Winnecke's comet in 1877 also give a sequence which add to the proofs that comets are swarms of meteorites. This comet was about 73,000,000 miles distant from the sun at perihelion, hence it did not get hot enough to give the bright iron lines seen in the comet of 1882. The first observation was made a day after perihelion. Hot carbon was then seen in conjunction with the dark bands due to manganese absorption. Seventeen days after perihelion hot carbon was still visible, but the dark manganese bands had been replaced by bright manganese, and nine days after this observation the spectroscope only showed

the existence of cool carbon. If the observations had been continuous, there is little doubt that hot carbon would have been seen some time during the nine days.

Halley's Comet.—This comet is remarkable as being the first which was shown to move in a closed orbit. In 1682 Halley compared the elements of a comet which appeared that year with those of two comets seen in 1607 and 1531, and found them identical. He therefore predicted that the comet would be seen in 1759, and it was seen. The comet has thus a period of about seventy-six years. Its next return is in 1910.

Encke's Comet.—In 1819 Encke discovered another periodic comet. Its orbit is much smaller than that of Halley's comet, and its period only three and a half years. It belongs to a class of comets having periods up to about ten years, and known as 'comets of short period.' A singular circumstance with regard to Encke's comet is that its period decreases by about two and a half hours every revolution. The theory generally accepted to account for this behaviour is that the comet has to pass through some resisting medium which diminishes its centrifugal tendency, and in so doing causes it to describe a smaller orbit. Another anomalous characteristic of this comet is that it contracts as it approaches the sun. Halley's comet undergoes a similar contraction.

Biela's Comet.—The second comet of short period was discovered by Biela in 1826. Its orbit very nearly intersects that of the earth, so that when the two bodies reach the point of intersection together a collision must occur. In 1846 the comet was seen to be double, and some remarkable changes were observed in the appearance of the two parts. The double comet was again seen in 1852, each part travelling in its own orbit round the sun. In 1866 the comet ought to have appeared, but it did not. It was due again in November, 1872, but a shower of shooting stars was seen when the earth was near the place where the comet ought to have been. The shower was repeated in 1885 and 1892, when the earth and the comet were similarly situated. From this coincidence it is generally believed that the meteoritic particles which produced the showers represent the result of the breaking up of Biela's comet.

Lexell's Comet.—A comet which appeared in 1770 was found by Lexell to have a period of about five and a half years. It was therefore expected to return in 1776. In this year, how-

ever, the relative positions of the earth and the comet's perihelion point rendered it impossible to observe the object. Before the next return in 1781, the comet passed very near to Jupiter, nearer in fact than the fourth satellite. The satellites were not disturbed by this encounter, but the comet must have had its orbit changed, for it did not appear in 1781, and has since been recorded as a lost comet. But there is more to be said on this point. Calculations showed that in 1886 the comet and Jupiter would occupy the same relative positions as in 1779, when the orbit was changed, and speculations were made as to what would be the result of the meeting. In 1889 a comet was discovered by Mr. Brooks, which subsequently divided into four parts. An investigation of the orbit led to the conclusion that Brooks's comet was the long-lost comet of Lexell brought again under observation by the attraction of Jupiter. Mr. Chandler has fully investigated the case, and finds as follows:—

(1.) The encounter of the comet with Jupiter in 1886 effected a complete transformation of the comet's orbit. Instead of the present seven years ellipse, it was previously moving in a large one of 27 years period.

(2.) Several months before reaching its perihelion, it passed, near the beginning of 1886, into the sphere of Jupiter's attraction, and was deflected into a hyperbolic path about the planet, and narrowly escaped being drawn into a closed orbit, as a satellite of Jupiter.

(3.) At the point of closest approach to Jupiter, May 20th, 1886, the comet was distant from it only about nine diameters of the planet, passing a little outside the orbit of the third satellite.

(4.) In 1779, and not before, the comet must have come so near to Jupiter as to pass under his control and experience a radical change of orbit at the point of longitude where Lexell's comet underwent its notable disturbance in that year. Moreover, the elements of Lexell's comet before the disturbance were strikingly similar to those found for Brooks's comet previous to 1886.

There seems to be little doubt that the two comets are identical, and the body is now known as the Lexell-Brooks comet.

QUESTIONS ON CHAPTER XI.

(1.) What are comets? (December, 1888.)

(2.) State what you know concerning the connection between comets and meteorites. (December, 1886.)

(3.) Describe a comet, and say what the spectroscope has taught us regarding the nature of these bodies. (December, 1882.)

(4.) How was the connection between comets and meteorites established? (May, 1887.)

(5.) Describe the general sequence of spectroscopic phenomena exhibited by comets in journeying round the sun.

(6.) Describe the general changes in the appearance of a large comet when passing from aphelion to perihelion.

(7.) State the spectroscopic reasons for believing that a comet is at its lowest temperature when at aphelion.

(8.) How have the tails of comets been classified?

(9.) Name the principal elements and some of the minerals found in meteorites.

(10.) State some of the chief results of recent researches on the spectra of meteorites.

(11.) Write a short account of Halley's and Biela's comets.

(12.) Describe fully the facts which led to the conclusion that Tempel's comet of 1865 is a swarm of meteorites.

CHAPTER XII.

STARS AND NEBULÆ.

Comparative Brightnesses of Stars.—The most noticeable fact concerning the stars is that they differ in brightness. Stars are classified into *magnitudes* by astronomers, those which appear among the brightest in the heavens being stars of the first magnitude, and each group containing stars less bright than the one before it. Stars of the sixth magnitude can only just be seen by the naked eye. To grasp stars fainter than this, a telescope or photographic plate is employed. Roughly speaking, the average first magnitude star is 100 times brighter than the average sixth magnitude star. This has led to the adoption of a fixed light-ratio of stellar magnitudes. If we take as unity the brightness of a sixth magnitude star, the brightness of a star of the fifth magnitude will be 2·51 times greater; a fourth magnitude is 2·51 times brighter than one of the fifth magnitude, and so on up to the

first magnitude. The interval between any two magnitudes is thus the fifth root of 100, that is, 2·51. In other words, it would take about two and a half stars of any magnitude to equal the brilliancy of a star in the next brightest group. In accurately stating magnitudes, fractions are employed. Thus a star of magnitude 5·5 is intermediate between the fifth and sixth magnitudes. A few stars in the heavens are brighter than the first magnitude. These are designated by negative numbers or fractions.

Number of Stars.—The number of stars visible to the naked eye in the whole heavens is about 6,000. Only half the celestial sphere can be seen at any time, and the number of stars which could be seen by the unaided eye on a clear night and counted is only about 2,500. Faint stars are far more numerous than stars visible to the naked eye. With a telescope less than three inches in diameter, Argelander, a German astronomer, observed and recorded the places of more than 300,000 stars. Within certain limits, the larger the aperture of a telescope the greater is the number of stars which can be grasped by it. The 40-inch telescope now being constructed in America will be able to grasp stars down to the 17th magnitude, that is to say, this telescope will reveal to an observer at least 100,000,000 stars. By inserting a sensitive plate in the telescope, in the place of the eye, stars and other celestial objects can be photographed. The number of stars which appear upon the plate increases with the duration of exposure. Indeed, the stars capable of being photographed are practically countless.

Photography of the Heavens.—In 1887 a scheme was formulated for making a photographic map of the heavens, and a number of astronomers are now taking part in the work. 'The entire map of the sky will, when finished, cover a globe seven metres (7·6 yards) in diameter. Two series of plates will be taken; one with a short exposure, showing stars down to the eleventh magnitude, and another containing stars down to the fourteenth magnitude. Each of the two plates must be exposed twice as a check against defects on the plate or specks of dust. The first series will form a catalogue of about 1,500,000 stars, and the second will run the number up to about 20,000,000. About 10,000 plates will be required to cover the whole sky surface, and, as four exposures have to be made on each region, 40,000 plates will have to present their sensitive films to the heavens before the work will be completed.'

Constellations.—The ancients fancied that they could distinguish the figures of men and animals outlined in the heavens, and gave to each star-group or constellation the name of the figure it was supposed to represent. Ptolemy, about 150 A.D., named 48 constellations after mythological characters. Though many more have been added by different astronomers from time to time, only about 60 constellations are now recognised. The zodiacal constellations are those through which the sun appears to pass, on account of the revolution of the earth. They are twelve in number. North of the zodiac occur about 27 constellations and south of it about 21. The visible stars have been found to be distributed in the different constellations, as follows:—

Magnitude	1	2	3	4	5	Total.
Northern Constellations	4	22	65	132	604	827
Zodiacal ,,	5	10	37	83	229	364
Southern ,,	11	26	63	157	654	911
Total ...	20	58	165	372	1,487	2,102

How Stars are designated.—In 1603 Bayer introduced the method of distinguishing individual stars in a constellation by Greek letters, giving the first letter of the alphabet, *Alpha* (written α) to the brightest star, *Beta* (β) to the next brightest, and so on through the whole alphabet. The genitive case of the Latin name of the constellation follows the Greek letter. Thus, α Lyræ, signifies the brightest star in the constellation of the Lyre, and α Canis Majoris, the brightest in the Great Dog constellation, and β Orionis a bright star in the constellation of Orion. After the 24 letters of the Greek alphabet have been exhausted, Roman letters are used. In both these methods the order of the letters follows the order of brilliancy, but on account of the fact that some stars have changed their brightness since they were named, it occasionally happens that the order is broken. Thus δ Ursæ Majoris is fainter than ϵ, ζ, and η of the same constellation. Flamsteed first began to give stars numbers in the order of their right ascension, irrespective of their brightness, and his method is frequently used. The ancients gave proper names to the brightest stars in the heavens. The brightest star in the Great Dog (α Canis Majoris) is called Sirius, Vega is the name of α Lyræ, Rigel of β Orionis, Aldebaran of α Tauri, and many other stars are similarly distinguished.

Catalogues of Stars.—Catalogues of stars are lists of stars arranged in the order of right ascension, and containing the declination and other data referring to the positions of stars. Various catalogues have been published by different authorities. The British Association Catalogue, abbreviated to B.A.C., contains the positions of 8,377 stars. Lalande also made a catalogue of stars, so did Argelander. In referring to either of these catalogues, it is usual to abbreviate the names of the observers to Ll. and Arg. respectively, and put after it the number of the star. Altogether, the celestial co-ordinates of between 800,000 and 900,000 stars are now known.

Determination of Distances of Stars.—The diameter of the earth's orbit is employed as the base line for the determination of the distances of stars. (Fig. 93.) A star is thus seen from two points separated by a distance of 186,000,000 miles. In spite of this, the angle subtended by the radius of the earth's orbit does not reach a single second of arc in the case of any star. Now, any length, whether an inch, or a mile, or 93,000,000 miles, subtends one second of arc at a point situated at 206,265 times that length. An inch subtends 1″ at a point 206,265 inches away; a mile subtends 1″ at a point 206,265 miles away. Hence, if a star had a parallax of 1″ it would be removed from the earth by 206,265 times the radius of the earth's orbit. Since, however, so large a parallax has not yet been accurately found, no star is so near to us as 206,265 × 93,000,000 = 19,182,645,000,000 miles. It will be understood from this that the determination of stellar parallax involves extremely accurate observation with the best of astronomical instruments. The two methods employed

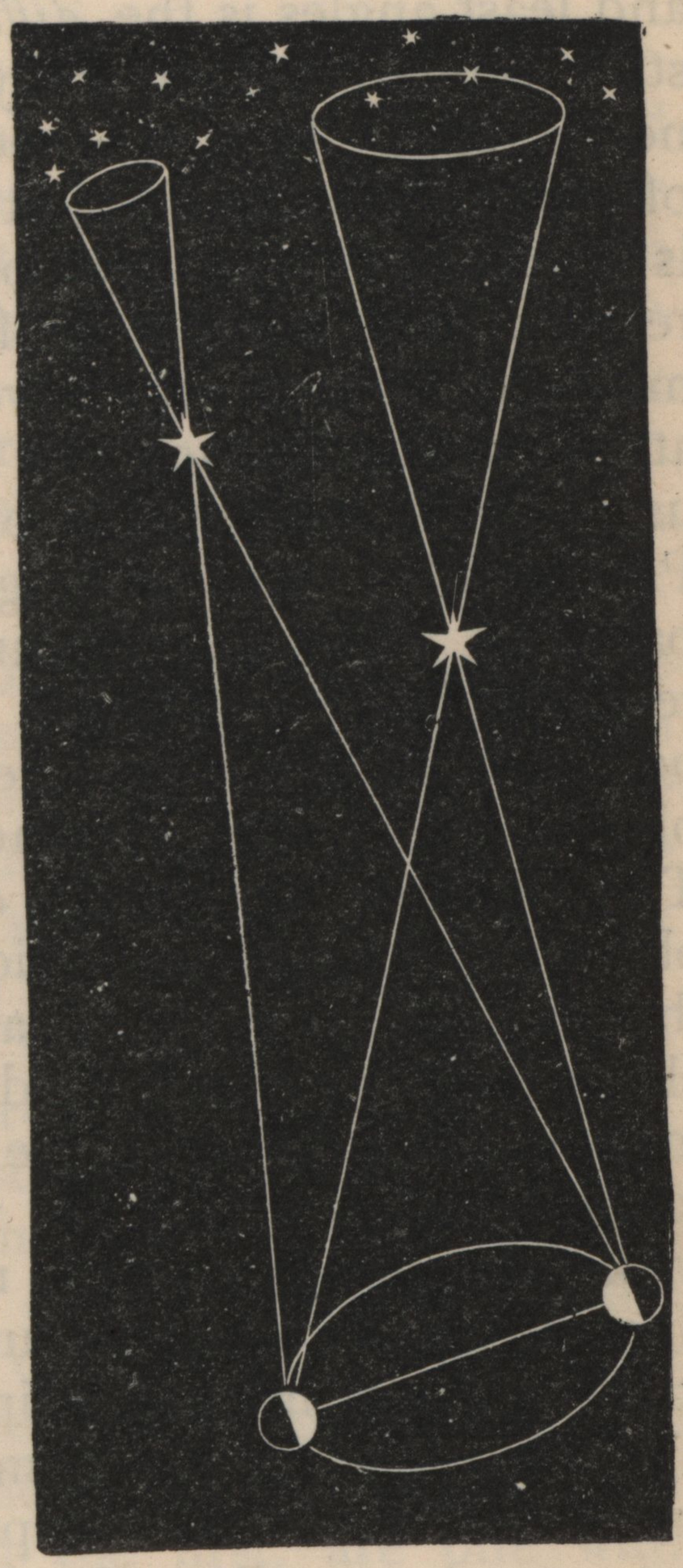


Fig. 93.

On account of the earth's orbital motion, each star describes a minute ellipse upon the celestial sphere in the course of a year.

are known as the *differential* and the *absolute* or *transit circle* method. In the differential method, the fact that there are a number of stars in the heavens almost in the same line of sight, and known as optical doubles is utilized. These stars are not really close together, but only appear so on account of their position. The relative positions of these stars are measured throughout the year. On account of the shift in the place of the earth, the aspect of the line connecting the optical double is continually changing. In other words, the angle contained between two lines, one drawn from each star to the earth, is different when the earth occupies different positions in its orbit. The difference between the greatest and least angles is the *difference* between the parallax of the two stars, though it is generally taken to represent the parallax of the nearer star. It is not necessary to confine observation to a pair of stars in the manner first suggested by Herschel. What is done is to measure the position of the star under observation with respect to a number of faint stars near it, and continuing the measures throughout the year. The faint stars are assumed to be at an infinite distance, and if the star under observation is nearer to us, it shows a slight shift of position relatively to them. Professor Pritchard has used photography in the determination of stellar parallax. The region surrounding the object whose parallax is required is photographed from time to time, and the relative positions of the stars are then directly measured upon the photographic plate, instead of measuring them in the telescope. The absolute or transit circle method consists in accurately observing the right ascension and declination of the star of which the parallax is required at different times of the year. After eliminating the effects produced by aberration, precession, proper motion, refraction, etc., the resulting positions of the star will be found to show a periodic variation. And if it were possible to make the measures with mathematical precision, and all vitiating effects were exactly understood, every star would be found to describe a minute ellipse upon the background of space. The ellipse would be a miniature representation of the earth's orbit. It would be comparatively large for the nearest stars, but much smaller for those more distant. The angular dimensions of the semi-major axis of the ellipse apparently described by a star is that particular star's parallax. It differs for different stars, and cannot therefore be confused with the semi-major axis of the aberration ellipse, which is the same for all stars.

The Distances of Stars.—The earth's mean distance from the sun is 93,000,000 miles. The nearest star is at more than 250,000 times this distance from us. About thirty stars have had their distances determined, and the following table shows some of the results:—

Name of Star.	Magnitude.	Distance in Astronomical Units.	Distance in Light Years.
a Centauri	0·7	250,000	4
61 Cygni	5·0	500,000	8
Vega	0·2	1,260,000	20
Aldebaran	1·0	1,700,000	27

The astronomical unit of distance is the distance of the sun from the earth. And it will be seen that even when this is used to express the distances of stars, the numbers obtained become inconveniently large. On this account, astronomers utilise the distance which light travels in a year (about six billions of miles) as the unit of stellar distance, and term it the *light year*. There is little doubt that a large number of stars are so far removed from the earth that their light takes hundreds, and perhaps thousands, of years to reach us.

Relation between Distance and Magnitude.—On the whole, it appears probable that bright stars are nearer the earth than fainter ones. But this is certainly not true in all cases, for the apparent brightness of a star is dependent upon the size of the luminous surface presented to the earth, and the intrinsic brilliancy of that surface, as well as upon distance from the earth.

Herschel made the assumption that brightness was merely a question of relative distance. In his words:—'Since it is evident that we cannot mean to affirm that the stars of the fifth, sixth, and seventh magnitude are really smaller than those of the first, second, and third, we must ascribe the cause of the difference in the apparent magnitudes of the stars to a difference in their relative distances from us; and on account of the greater number of stars contained in each class, we must also allow that the stars of each succeeding magnitude, beginning from the first, are one with another farther from us than those of the magnitude immediately preceding it.'

The Milky Way.—This is the name given to the large, irregular zone of light which encircles the whole celestial sphere. The breadth and brightness of this zone vary in different parts of

the heavens. In some parts it is only four or five degrees wide, in others its width is as much as fifteen degrees. Near the constellation of the Scorpion, the Milky Way or Galaxy divides into two branches. The Galaxy does not coincide with the ecliptic or the equator, though it forms almost a circle in the heavens. The galactic equator cuts the ecliptic at an angle of about 55°, and the galactic poles are the points 90° north and south of it.

Distribution of Stars.—Observation shows that the Milky Way is composed of an immense number of small stars. From this it is evident that by far the greater number of stars in the heavens are congregated near the Milky Way. Herschel counted the stars visible in the field of view of the same telescope directed to different parts of the heavens, and the following table shows the average result for several galactic latitudes:—

Distance from Galactic Equator.	Average Number of Stars Visible.
90°	4
75	5
60	6
45	10
30	18
15	30
0	122

It appears, therefore, that there is a rapid increase in the number of stars as the galactic equator is approached. To account for this, Herschel supposed that 'the stars of our firmament, instead of being scattered in all directions indifferently through space, form a stratum of which the thickness is small in comparison with its length and breadth, and in which the earth occupies a place somewhere about the middle of its thickness, and near the point where it subdivides into two principal laminæ, inclined at a small angle to each other. For it is certain that, to an eye so situated, the apparent density of the stars, supposing them pretty equally scattered through the space they occupy, would be least in a direction of the visual ray perpendicular to the lamina, and greatest in that of its breadth, increasing rapidly in passing from one to the other direction, just as we see a slight haze in the atmosphere thickening into a decided fog bank near the horizon by the rapid increase of the mere length of the visual ray.' (Outlines of Astronomy, Sir J. Herschel.)

Hence, according to this theory, the sun and planets are situated near the inner edge of an annulus or ring of stars, and the Milky Way is the projection of this system upon the celestial sphere as seen from a point within it.

Proper Motions of Stars.—When the positions of stars are compared after a long interval of time, changes are found which can only be due to real motion across the celestial sphere. Such motions are termed *proper* motions to distinguish them from the *apparent* motions, which are but reflections of the movements of the earth. Every star in the sky is rapidly moving in one direction or another, but on account of the enormous distances of these objects, the movements do not manifest themselves until they have been going on for a considerable time. A faint star numbered 1830 in Groombridge's catalogue, and referred to as 1830 Groombridge, has the largest proper motion, viz., seven seconds of arc (7″) in a year. The nearest star, α Centauri, has a proper motion of nearly 4″ in a year. When the distance of a star is known as well as its proper motion, the velocity in miles per annum across the line of sight can be calculated. It has been found that 1830 Groombridge is moving at the rate of 200 miles per second in a direction perpendicular to the line of sight, and α Centauri at the rate of about 440,000,000 miles per annum. These numbers tell us nothing about the absolute velocities of the stars in question, and it is only when the velocity with which a star is moving towards or away from the earth, as well as its velocity in a direction perpendicular to this, are known, that the resultant of these velocities, in other words, the true rate of movement in space, can be calculated.

The Apex of the Sun's Way.—The sun, like other stars, is in motion, carrying through space its planets and their satellites. When the proper motions of hundreds of stars are investigated, there appears to be a general movement away from a particular part of the sky and towards a point diametrically opposite. This result is produced by the sun's motion. The point from which the star-motions appear to radiate is the point towards which the sun is moving—the apex of the sun's way—while that towards which the stars as a whole converge marks the anti-apex or quit. From a number of determinations the apex is found to be in the constellation Hercules. An analogy, though not a very exact one, is found in the fact that, when walking through an avenue of trees, the trees in front appear to open out while those behind close up.

Double Stars.—Many stars which appear single to the naked eye are seen to be made up of two when viewed telescopically, and are known as double. Until about a century ago, double stars were thought to be an optical coincidence produced by two stars lying nearly in the same line of sight at different distances from the earth. Herschel found, however, that the direction of the line joining the two components of a pair of stars changed in the course of years, and further observation led to the discovery that such stars moved round their common centre of gravity in a similar manner to the movement of the earth and moon. Double stars in which orbital motion has been detected are thus physically connected, and not merely optical doubles. They go by the name of *binary* stars. About 10,000 double stars are known, and in about 400 cases a change in the direction of the line connecting the doubles has been observed. The periods of rotation vary from 15 to about 1,500 years. When the angle subtended at the earth by the semi-major axis of a double-star orbit is known, and also the parallax of the binary, the length of the semi-major axis in astronomical units can be found by dividing the former by the latter angle. Thus, the semi-major axis of the orbit of α Centauri subtends an angle of $17''{\cdot}25$, and the parallax of the double is $0''{\cdot}75$; hence the length of the axis is $\frac{17{\cdot}25}{0{\cdot}75}$, that is, 23 astronomical units. Taking the unit as 93,000,000 miles, the distance between the two stars which make up α Centauri is $23 \times 93{,}000{,}000$, that is, 2,139,000,000 miles. When the period as well as the distance between the components of a double star has been found, the combined mass of the pair can be calculated by the application of Kepler's third law. The equation employed is as follows:—

$$\text{Combined Mass} = \text{Mass of Sun} \left(\frac{d^3}{p^2}\right)$$

in which d represents the length of the semi-major axis in astronomical units, and p the period in years. Applying the equation to α Centauri, we have:—

$$\text{Combined Mass} = \text{Mass of Sun} \left(\frac{23^3}{77^2}\right)$$

And from this we find that the sum of the masses of the components is twice the mass of the sun.

Multiple Stars and Clusters.—Besides the stars which can be resolved into two, a large number have been found to consist

Fig. 94. Views of Star Clusters.

of three, four, or more, all physically connected, as evidenced by their motions. These go by the name of multiple stars. Groups or clusters containing hundreds of stars are also seen in the sky. The most conspicuous cluster to the naked eye is the Pleiades, in which from six to ten stars can be counted. Another cluster called the Præsepe in the constellation of Cancer is seen to be made up of numerous stars, when viewed with a field-glass. Other clusters, which appear like patches of mist when seen by the naked eye or a small telescope, are broken up into innumerable stars when a large instrument is employed, and afford one of the most beautiful of celestial sights. (Fig. 94.)

Nebulæ.—We have said that there are hazy patches in the heavens which can be resolved into separate stars by using a sufficiently powerful telescope. There are also cloud-like bodies which cannot be broken up into stars, and to such the name of *nebulæ* is given. For a long time it was supposed that a nebula was a star cluster very far removed from the earth, and therefore consisting of a large number of separate stars, but the spectroscope has shown that this is not the case.

Distribution of Nebulæ.—Stars are far more numerous near the Milky Way than in other parts of the heavens. Nebulæ, on the other hand, are fewest near the galaxy and most numerous away from it. The constellation Virgo is the region richest in nebulæ.

Forms of Nebulæ.—Some nebulæ are irregular in form and cover an enormous area of sky. Others are more or less regular in outline. Many of the small nebulæ have exactly the same appearance as a comet at a great distance from the sun. There are also double, triple, and multiple nebulæ, as in the case of stars. Nebulæ are classified according to their form as follows :—

(1.) *Irregular Nebulæ.*—An example of this type is the Great Nebula of Orion. With a field-glass or small telescope four stars are seen close together and forming a 'trapezium.' These are involved in the nebula and have most probably been condensed out of the nebulous material. Another large irregular nebula surrounds the star η Argus in the southern hemisphere. Photographs of the Pleiades have shown that the stars are involved in an irregular mass of nebulosity.

(2.) *Annular Nebulæ.*—This is rather a rare type. The most remarkable member is situated between β and γ Lyræ. It has the form of an oval ring surrounding a very faint disc of nebulosity, in the centre of which a brighter part occurs.

(3.) *Elliptic Nebulæ.*—When an inclined ring is observed it appears elliptical in form. It is therefore generally supposed that spindle-shaped or elliptical nebulæ, such as that in the constellation Andromeda, are ring nebulæ seen slantingly. Could we observe the Andromeda nebula from a point perpendicular to the plane of the ring, we should see a system very similar to that of the planet Saturn.

(4.) *Spiral Nebulæ.*—A few nebulæ have a spiral appearance, like a 'Catherine-wheel' whirling round and round. The most remarkable member of this class is the Spiral Nebula in Canes Venatici.

(5) *Planetary Nebulæ.*—Nebulæ of this type present a more or less circular disc of nearly the same brightness in all its parts. Globular nebulæ are similar discs surrounded by fainter nebulosity.

(6) *Nebulous Stars.*—A few stars are surrounded by nebulosity, and sometimes a wisp of nebulous material is attached to a star like the tail of a comet, thus earning for themselves the name of *cometic nebulæ.* The forms of nebulæ appear to merge one into the other. Thus, planetary nebulæ pass by gradations into globular nebulæ and then into nebulous stars of all kinds, some appearing like nebulæ with a small nucleus in the centre; while others have but a small ring of nebulosity round them. In fact, though we cannot trace the growth of a single nebula, it is possible to trace in different nebulæ all the stages from an irregular patch of mist to single, double, or multiple stars, or clusters of stars.

Variable Stars.—A number of stars periodically vary in brightness, reaching a maximum brilliancy, then diminishing to a minimum, and brightening again to their former condition. The interval between two successive maxima is known as the *period* of the variable star. In addition to the regular variability, stars are subject to irregular fluctuations of brightness. Stellar variability can be classified as follows:—

(1.) Variables of Long Period.—In this class the period of variability extends over several months. A star called Mira (The Wonderful) in the constellation Cetus, and

designated as *o* Ceti, is a good example of the variations which occur. At the time of greatest brilliancy, this star appears as bright as a star of the first or second magnitude. A few days later, it fades away to a star of the ninth magnitude, quite beyond our range of vision. The interval between two successive maxima is 333 days.

(2.) Variables of Short Period.—Stars of this class have the same brightness during most of the period, but suddenly lose their brilliancy for a few hours and then as suddenly regain it. Algol or β Persei strikingly exhibits a variability of this character. Its period is rather less than three days and its range from the second to the fourth magnitude. For about two and a half days the star is of the second magnitude. It then loses five-sixths of its light in four hours, shines like a star of the fourth magnitude for a quarter of an hour, and then regains its former brilliancy in another four hours. Only 13 variable stars of the Algol type are known.

(3.) Variables of the β Lyræ Type.—Stars of this type have subsidiary maxima and minima in addition to the chief ones. They gradually rise and fall in brightness throughout the whole period. β Lyræ exhibits two maxima and two minima extending over a period of 13 days.

There are other kinds of stellar variability, though the bodies exhibiting the fluctuations are not sufficiently numerous to justify the erection of a special class for them. The star η Argus in the southern hemisphere appears to sink from the first to the eighth magnitude in about 70 years, and a star in Cepheus has a period of 73 years. Since, however, these variations extend over so many years, it is doubtful whether the stars really possess a regular period. There is evidence that a few stars have changed their brightness since they were first recorded, but nothing is accurately known on this point. It is usual to indicate by the letter R the first variable discovered in a constellation; thus, R Leonis is a variable in the constellation Leo. The next discovered variable takes the letter S, and so on to the end of the alphabet.

Explanations of Stellar Variability.—To explain the periodic variations in the brightness of stars like Mira Ceti, it has been suggested that the objects are in rotation and alternately present a bright and a dark side to the earth. The variability of stars of the Algol type is explained by supposing that a dark

body revolves round the primary star, and periodically eclipses its light. Professor Lockyer has shown that many stars are, in all probability, swarms of meteorites. On this idea he has been led to adopt the following causes of variability.

'*Regular Variability*.—All regular variability in the light of cosmical bodies is caused by the revolution of one swarm or body round another (or their common centre of gravity).'

'In the case of the revolution of one swarm round another an elliptic orbit is assumed, and the light of maximum is produced by collisions among the meteorites at periastron. In the case of the revolution of a swarm round a condensed body, the light of *maximum* is produced by the tidal action set up in the secondary swarm.'

'In the case of one condensed body revolving round another, the light of *minimum* is caused by an eclipse of one body by the other. This can only happen when the plane of revolution of the secondary body passes very nearly through the earth.'



Fig. 95. Lockyer's explanation of stellar variability of the Mira Ceti type.

Irregular Variability.—All irregular variability in the light of cosmical bodies is caused (*a*) by the revolution of more than one swarm or body round another (or their common centre of gravity), or (*b*) by the interpenetration of meteoritic sheets or swarms. In the case of the revolution of more than one swarm round another in elliptic orbits, the irregular maxima are caused by differences of period and periastric conditions.'

Professor Lockyer's explanation of the Mira Ceti type of variability is illustrated by Fig.95, which shows two swarms of meteorites, one revolving round the other in an elliptic orbit. When the two swarms cross each other, at periastron, the collision of individual meteorites causes an increase of luminosity, and as the smaller swarm passes away the meteorites return to their former temperature.

Evidence supporting Theories of Variability.—If the Mira Ceti type of variability is due to the revolution of meteor swarms, it should be expected that at maximum, when the temperature is increased by the increased number of collisions, some of the constituents of the meteorites should be volatilised. The spectrum ought, therefore, to undergo changes, and this is precisely what happens. At maximum, bright lines, chiefly due to hydrogen, are added to the star spectrum, thus giving considerable support to Professor Lockyer's theory. Indeed, the appearance of these bright lines on a spectrum like that of Mira Ceti can be taken as an indication of a star's variability, and this criterion has never been known to fail. Professor Pickering has well investigated the case of Algol. He photographed his spectrum a number of times during a period and found no difference except that due to difference of brightness. This, of course, is the result which would be expected, as the star which eclipses Algol has no light of its own. The theory has also been considerably supported by some recent spectroscopic researches made by Vogel at Potsdam. Algol has been proved to alternately move towards and away from the earth in a period coincident with that of its variation in light. Seventeen hours before a minimum, when the dark companion is rushing forward to obstruct the light of Algol, the star itself is being swung back. In a similar manner, after the dark companion has passed in front of the star, it moves away and causes Algol, which is situated on the opposite side of the common centre of gravity, to swing forward. The velocity of approach and recession indicated by the spectroscope is twenty-seven miles per second.

New Stars.—What is a new star, or a 'Nova,' as astronomers call the phenomenon? There are millions of stars shining in space which are never seen by the unaided eye; millions more, too faint to be grasped by the most powerful telescope manned with the best observer, leave their impression upon the photographic plate, and doubtless there are just as many bodies rolling and shining in space, at immeasurable distances, or emitting only non-luminous radiations, as all those which have, up to now, revealed their existence. Thus, as old methods of research are perfected, and optical discoveries are utilised, more light is obtained and deeper soundings of the universe are rendered possible. But although by such means bodies demonstrate their presence in what may previously have been considered as a dark space in the sky, the term 'new star' is not applied to them. It is reserved for those which flash out in a portion of the immense void we call space, and, after acquiring a short-lived brilliancy, sink back into the obscurity from which they came. Such objects are not now looked upon by astronomers merely as curiosities, to be considered as freaks of nature and nothing more; for they considerably extend our knowledge of the constitution of the universe, of the changes which accompany the birth, life, and death of worlds.

The New Stars of 1572 and 1604.—In 1572 a new star appeared in the constellation Cassiopeiæ. When first observed it surpassed Sirius in its brilliancy, and even rivalled the splendour of the planet Venus. The star took about fifteen months to sink from its grandeur to invisibility, and, as it diminished in magnitude its colour merged from white, through yellow and red, to a leaden hue. Another new star shone out upon our benighted world in 1604. It was said at first to be as bright as Jupiter, and was visible for about a month longer than the new star of 1572. Many other bodies of the same class have been noticed from time to time, but none have matched the splendour of these two. And doubtless hundreds of new stars, whose births are unrecorded, have added their light to that of the innumerable host which fill the sky; have lived and had their day, unknown to the world. In pre-telescopic times only the objects which forced themselves upon the vision of mankind by the effulgence of their blaze were likely to be discovered. Others would be passed by unnoticed.

The New Star of 1866.—From the new stars of 1572 and 1604, of which Tycho Brahe and Kepler, respectively, left circumstantial accounts, we pass to the one that appeared in the constel-

lation Corona in 1866. When this sent out its beams, astronomers had learned to use the spectroscope to determine the constitution of the heavenly bodies. It was natural, therefore, that almost directly after the star had been noticed an attempt should be made to analyse its light. And the coloured strip, into which the prisms decomposed the star-rays, was seen to be entirely different from any previously observed. The interpretation of the radiations was to the effect that hydrogen existed in the star's atmosphere in a state of incandescence. Carbon also appeared to be one of the constituents, and a ray—which is so constantly seen when the cloud-like masses in space are subjected to analysis, that it is called the 'nebula line'—glimmered in the spectrum of the body under examination. This was a fact worth recording. It established a relationship between stars and nebulæ, and is therefore of the highest importance. The star faded gradually, and its spectrum became simpler, until finally only a single representative of incandescent hydrogen remained.

The New Star of 1876.—Ten years after the appearance of the new star in the constellation of the Crown, one was discovered in that of the Swan; and a battery of telescopes, armed with spectroscopes, was soon directed to it. The analyses showed that brightest among its emanations were the ubiquitous radiations indicative of hydrogen, whilst other brilliant rays demonstrated the presence of the elements carbon, sodium, iron, and lead. But the most important line of all was one in the position of that which characterises nebulæ. As the star slowly diminished in brilliancy, all the rays, with the exception of this, suffered a corresponding decrease in intensity and faded away as the vapours they represented cooled down. The decrease of temperature, which prevented the elements in general from existing in an incandescent state, seemed to favour the development of the ray which connected the star with nebulæ. This line increased in brilliancy whilst all the rest were waning, and about eleven months after discovery the complex spectrum had entirely disappeared, the new star had become a very faint nebula, and, like many of the class of bodies to which it had been degraded, all its light was concentrated by the prisms into a single line. Upon any possible supposition the temperature at this time must have been lower than at the time of maximum brilliancy. And since the facts show that the new star in question cooled down to a body having nothing to distinguish it from a nebula, the idea that nebulæ represent the hottest denizens of space must be abandoned.

The New Star of 1885.—Nebulæ are really the most interesting objects in the heavens. Worlds seem to be formed by the condensation of the material of which these fleecy masses are made up. Hence, when it was announced in 1885 that a strange brightening could be distinguished in the centre of the Great Nebulæ in the constellation of Andromeda, it was thought that the time had arrived when some considerable additions to our knowledge might be obtained. And, although the anomalous luminosity did not attain any marked brilliancy, some new information was gained. An examination of the quality of the light emitted by the new star showed that carbon was chiefly responsible for its luminosity. But the fact of importance brought out by the observations was that the luminous radiations under consideration were precisely similar to those which distinguish comets. Since 1885 the rays of the Nova have been detected in the Andromeda nebula itself. The conviction is therefore forced upon us that the new star was but a hotter portion of the nebula, the increased temperature accentuating the radiations indicative of carbon.

Now let us sum up the facts. We have first that the Nova of 1866 exhibited a ray like that which is the family crest, as it were, of nebulæ. Next, the Nova of 1876 emitted the same rays as those which characterised a large number of nebulæ, and, as it diminished in brilliancy, and presumably decreased in temperature, the 'nebula line' increased in brightness. And, finally, the Nova of 1885 emitted light of the same nature as that given out by a comet when fairly near the sun. Obviously, then, new stars are intimately connected with nebulæ and with comets.

The New Star in Auriga.—Dr. Thomas D. Anderson, an amateur astronomer of Edinburgh, directed his 'inquiring eye' to the constellation Auriga on several occasions towards the end of January, 1892, and on the last day of that month satisfied himself that a strange star was visible in the portion of the sky under observation. The simplicity of his observing means will afford encouragement to even the humblest of amateurs. In a letter in *Nature*, of February 18, Dr. Anderson says: 'My knowledge of the technicalities of astronomy is, unfortunately, of the meagrest description; and all the means at my disposal on the morning of the 31st ult., when I made sure that a strange body was present in the sky, were Klein's "Star Atlas" and a small pocket telescope which magnifies ten times.' Having found that the star was not indicated in the map, Dr. Anderson sent an anonymous postcard to Professor Copeland, the Astronomer Royal of Scotland,

announcing the discovery. The latter astronomer verified the discovery, and the welcome news was soon telegraphed to Observatories all over the world. The appearance of this little stranger caused as much commotion in astronomical circles as is usually supposed to be developed when a little speck of humanity is ushered into the world. Professor Pickering, of the Harvard College Observatory, U.S., looked up his photographs of the region of the sky in which the new star was located, and found that the body had left its impression on negatives taken so far back as December 1, 1891. So, instead of bursting forth suddenly, as was at first supposed, the star had registered its birth and lived a span of life before the day on which it found itself famous. But this is not to be wondered at. It is more strange that such an inconspicuous body should ever have been noticed. On February 1, the world that had been called forth from a void was but of the fifth magnitude. It could, therefore, only be seen with the naked eye when the observing conditions were good.

Professor Copeland made the first analysis of the new star's light on February 2nd. Rays of hydrogen and sodium were recognised, and other lines were seen, but not identified. February 3rd was fortunately a fine night, and full advantage was taken of it by Professor Lockyer at South Kensington. On this date the star was made to weave its pattern on a photographic plate, and from the positions of the impressed rays the quality of the light was determined. The existence of incandescent hydrogen and sodium was confirmed, carbon and calcium were detected, and the line which is characteristic of the spectrum of nebulæ was looked for and found in its place. So far the new body did not appear to be different from others of its class; but on February 7th a photograph was taken, under Professor Lockyer's direction, which enlarged our views considerably. The new fact brought to light by this picture was that the bright rays indicative of hydrogen were accompanied by dark rays on their more refrangible side. A word of explanation is necessary here. When a beam of light falls upon a prism of glass it is broken up into a rainbow-coloured strip, and at the same time is bent or refracted out of its original direction. The red end of this strip is not bent so much as the violet one, and is said to be the less refrangible end of the spectrum. The violet end of a spectrum is termed the more refrangible end. Professor Lockyer's discovery, then, was that the spectrum of the star showed bright hydrogen lines in testimony of the incandescence of this element, whilst dark lines proved that absorption was

taking place. But if both the bright and the dark lines are due to hydrogen why are the latter nearer the violet end of the spectrum than the former? The reason will be best understood from an analogy. Most individuals of an observant nature must have noticed that the shriek of the whistle of a locomotive appears to increase in pitch if the locomotive is approaching, but if the movement is away from the place of observation, the pitch is lowered. In the former case the number of vibrations which fall upon the ear and produce the sensation of sound is increased, and in the latter it is diminished. Now apply the analogy to a star spectrum.

When a star is at rest relatively to the earth the lines of a particular substance, *e.g.*, hydrogen, occupy a certain position. If the star move towards the earth the same lines are shifted towards the violet end of the spectrum; their pitch, so to speak, is increased. Motion away from the earth causes the lines to be displaced towards the red end of the spectrum, causes the pitch to be lowered. The interpretation of Professor Lockyer's observation is, therefore, that the new star is made up of two bodies; one, giving a spectrum of dark lines, is moving towards the earth, and the other is receding. The relative velocity of these two bodies is something like 500 miles per second. The observations have been confirmed by Professor Pickering and Professor Vogel at Potsdam, so there seems no room to doubt that the luminosity has been caused by collisions of some kind. And the rapid fading of the star proves that large bodies could not have collided. The enormous amount of light and heat which would result from such an encounter was worked out by the late Dr. Croll. He said, 'Suppose two bodies, each half the mass of the sun, moving directly towards each other with a velocity of 476 miles per second. These bodies would, in virtue of that velocity, possess energy which, converted into heat by the stoppage of their motions, would suffice to maintain the present rate of the sun's radiation for a period of 50,000,000 years.' The whole of the facts with regard to Nova Aurigæ and other new stars appear to confirm Professor Lockyer's suggestion that the luminosity is produced by the collision of two swarms or streams of meteors in space.

Cause of the Appearance of New Stars.—Newton held in the Principia that new stars were produced by the collision of comets. Another view is that the phenomena are caused by glowing vapours bursting from a body covered with a non-luminous crust. It has also been suggested that

if by some means a mass of hydrogen is evolved in a star, its sudden ignition would increase considerably the brightness of the star.

These considerations, plausible though they may appear, are open to one objection, namely, that the heat generated would be sufficient to sustain the light of the star for thousands of years, and certainly it would be impossible for it to cool so quickly as to fade away altogether, sometimes in the course of a few days. The theory which best explains all the phenomena presented by new stars is that propounded by Professor Lockyer, and is similar in some respects to that put forth by Newton. The difference lies in the fact that Newton looked upon new stars as having their origin in the heat produced by the impact of two bodies, whilst Professor Lockyer's theory is that they are due to the meeting of two swarms of meteorites in space. In the latter case, when these swarms or groups of stones are passing one another a number of collisions would take place and consequently a rise of temperature. The temperature would be higher according as the colliding swarms were more or less condensed, and the increase in luminosity would last just as long as the two swarms of stones were rushing past one another. If the crowd of stones in each swarm were close together, then the collision would be more sudden, and a new star would be formed which may only last for a few days; but if, as is the case with a few new stars, the luminosity lasts for some time, the two swarms of meteorites engaged in producing this phenomenon would have the individual meteorites which made up the swarm far apart. The outliers of the swarms would first collide, there would be a gradual increase of temperature until the most condensed parts of each swarm had passed, and then a gradual decrease to extinction. The objection to Newton's theory does not apply to this. It is found that the light of new stars is of a comparatively low temperature, and not that high temperature which would be produced by the direct impact of two large masses. The stones are not dissipated entirely into vapour, for the light seen emanates from the elements in them which are most easily volatilized. In all new stars that have been examined, light due to hydrogen gas has been seen, and this is exactly what would be seen first on the meeting of two meteor swarms. It is probable that little direct impact takes place as the two swarms pass; the stones more often must graze against each other, enough heat being generated to turn into vapour the most volatile of their constituents.

Coloured Stars.—Though to the casual observer the stars appear to present the same aspect, an intelligent glance at the sky shows at once that the light of stars differs in colour. Aldebaran, the brightest star in the constellation Taurus, has a ruddy colour, so has the star Betelgeuse near it. Capella and Rigel have a bluish tint, but do not differ considerably from Sirius, Vega, and Regulus, which are generally referred to as white stars. A remarkable fact concerning double stars is that the components usually differ in colour. 'Many of the double stars,' says Sir J. Herschel, 'exhibit the beautiful and curious phenomena of contracted or complementary colours. In such instances, the larger star is usually of a ruddy or orange hue, while the smaller one appears blue or green.' When the components are equal, there is no difference of colour. The smaller star always has a tint nearer the violet end of the spectrum than that of the larger companion. This is what would be expected if the two bodies once formed a single mass. It is possible, of course, that large stars may take unto themselves smaller ones in a similar manner to that in which the sun annexes comets. On these points Professor Lockyer finds 'in nearly all cases the components of a binary star can be shown with much probability to have had their origin in double nebulæ. There are exceedingly few cases in which it seems at all likely that the companion is an addition of a cometary nature, and it is possible that even these few exceptions may be due to errors of observation. This, then, strengthens the view that in the case of regular variable stars of Group II. (Mira Ceti type) we are in presence of the formation of a double star, at an early period in its history when the two swarms are at times, so to speak, in contact. When the variability is not regular, we are in presence of the formation of a multiple system.'

Facts concerning the Solar System.—A study of the elements of the solar system leads at once to the conviction that the bodies have not been accidentally brought together. The planets move round the sun in nearly circular orbits in the same direction, and almost in one plane, at distances from the sun connected by a simple law. With the possible exception of Uranus and Neptune the planets rotate in the same direction as they revolve, and their equatorial planes lie nearly in the plane of revolution; and, with the same possible exceptions, the satellites move in the same way in the equatorial planes of their primaries. These facts have led to the formulation of a hypothesis which should account for the growth of our system.

The Nebular Hypothesis.—Kant and Swedenburg made speculations as to the genesis of the solar system, and Laplace developed the hypothesis mathematically. It is supposed that ages ago the sun existed in the form of a nebula, extending probably beyond the orbit of Neptune. This solar nebula was supposed to consist of incandescent gas. The shape of such a mass of glowing gas would be spherical, and a motion of rotation would be set up in it. As the nebula cooled, it would contract. The rotational velocity would thereby be increased, and eventually the centrifugal tendency at the equator would become equal to the gravitational attraction, and a ring of matter would be left behind. This ring would for a time behave like the rings of Saturn and revolve round the central body, but finally it would condense into a single mass possessing similar motion. This mass might then go through the same changes as its parent, and shed rings which would furnish a system of satellites. The hypothesis is generally accepted by astronomers, though several points cannot be explained by it. It is also applied to the heavens to account for the evolution of stars from nebulæ.

The Constitution of Nebulæ.—Laplace's idea that a nebula is a mass of glowing gas is, to say the least, doubtful. Observations show that hydrogen exists in nebulæ, but this by no means proves that the bodies are gaseous. In 1871, Professor Tait made the suggestion that nebulæ are in some manner associated with meteorites and not masses of gas at all, and M. Faye has shown that a nebulæ may just as probably consist of a cloud of stones as a mass of gas. In recent years Professor Lockyer has considerably developed the matter. He believes that nebulæ are the coolest bodies in the heavens—swarms of meteorites just beginning to condense. Their luminosity is due to the vapours driven out of the meteorites by increased temperature due to collisions. Much can be said in favour of this theory. In the first place, it is generally believed that comets are swarms of meteorites, and comets frequently present exactly the same appearance as some nebulæ. What is more, comets have exhibited the characteristic line of a nebula in their spectra when near their aphelion point, and therefore at a low temperature. In describing comets, it was shown that they are drawn into our system by the attraction of the sun and planets. According to Professor Lockyer, comets are small patches of nebulous material annexed from outer space.

Lockyer's Temperature Curve.—The meteorites in a nebula or comet have their paths diminished by collisions, so the mass, as a whole, becomes hotter and hotter, and finally the meteorites will have pounded one another into vapour. The highest temperature will then have been reached. As this globe of vapour cools, its atmosphere changes. At the highest temperature hydrogen is the predominant feature. When the condition of our sun has been reached hydrogen loses its supremacy, and iron most strikingly manifests itself. The final change is when the ball

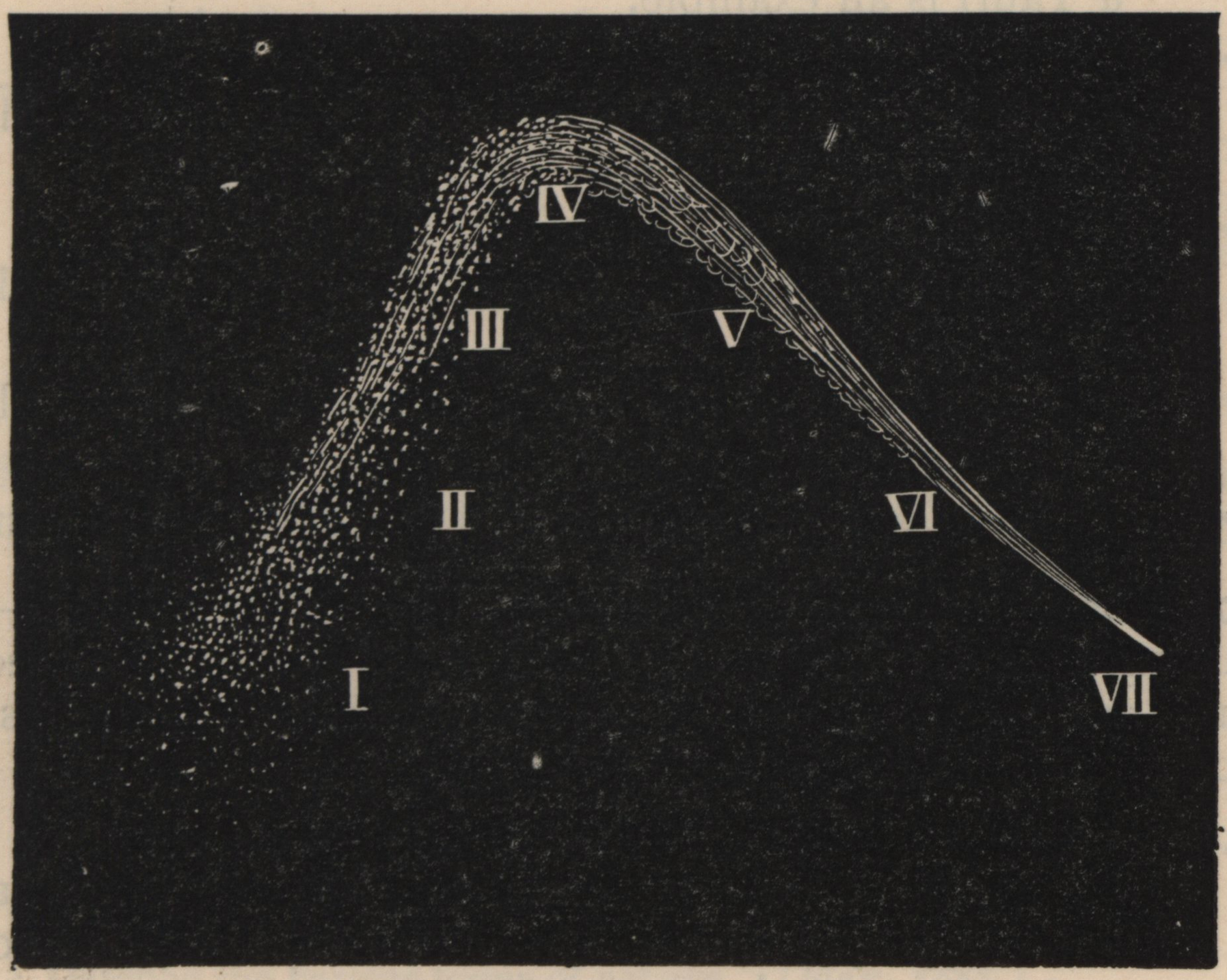


Fig. 96. Lockyer's Temperature Curve. The numerals show the positions of the different groups upon the curve.

of vapour has become consolidated into a body like the earth, with an atmosphere of nitrogen, oxygen, and water-vapour,—or the moon, with no atmosphere at all. Possibly after this some action occurs whereby such dark bodies break up into meteorites and so complete the cycle of changes. The grouping of all bodies in the universe according to their temperature is illustrated by Fig. 96. The origin of all these groups is ascribed by Professor Lockyer to meteoritic condensation. In making such a classification, the great difficulty is to determine the characteristic spectra of each

group. The grouping, according to the meteoritic theory, is as follows:—

Group I.—Nebulæ, stars like γ Cassiopeiæ, and comets with bright lines seen at low temperatures.

Group II.—Bodies with radiation of carbon flutings and absorption of some metallic flutings. Certain stars, *e.g.*, α Orionis, and some comets near the sun, are included in this group.

Group III.—Fluting absorption replaced by line absorption. α Tauri is an example.

Group IV.—Bodies showing very few lines other than those due to hydrogen absorption. This indicates the highest temperature. Sirius and Vega are examples.

Group V.—Reduction in the absorption of hydrogen. Considerable absorption of iron. The sun and Capella are examples.

Group VI.—Carbon absorption predominant. 152 Schjellerup is an example.

Group VII.—Dark planetary bodies like the earth and moon.

Conclusions from Researches on Meteorites.—After discussing a mass of facts, and observing the spectra of meteorites under a number of conditions, Professor Lockyer stated his conclusions, and among them are the following:—

(1.) All self-luminous bodies in the celestial spaces are composed of meteorites, or masses of meteoritic vapour produced by heat brought about by condensation of meteor-swarms due to gravity.

(2.) The spectra of all such bodies depend upon the heat of the meteorites, produced by collisions, and the average space between the meteorites in the swarm, or, in the case of consolidated swarms, upon the time which has elapsed since complete vapourisation.

(3.) The existing distinction between stars, comets, and nebulæ rests on no physical basis.

(4.) New stars, whether seen in connection with nebulæ or not, are produced by the clash of meteor-swarms, the bright lines seen being low-temperature lines of elements, the spectra of which are most brilliant at a low stage of heat.

(5.) Most of the variable stars which have been observed belong to those classes of bodies, which I now suggest are uncondensed meteor-swarms, or condensed stars in which a central, more or less solid condensed mass exists. In some of those having regular periods the variation would seem to be partly due to swarms of meteorites moving round a bright or dark body, the maximum light occurring at periastron.

(6.) The spectrum of hydrogen seen in the case of the nebulæ seems to be due to low electrical excitation, as happens with the spectrum of carbon in the case of comets.

(7.) Meteorites are formed by the condensation of vapours thrown off by collisions. The small particles increase by fusion brought about again by collisions, and this increase may go on until the meteorites may be large enough to be smashed by collisions, when the heat of impact is not sufficient to produce volatilisation of the whole mass.

(8.) Beginning with meteorites of average composition, the extreme forms, iron and stony, would in time be produced as a result of collisions.

QUESTIONS ON CHAPTER XII.

(1.) State what you know about nebulæ. (May, 1889.)

(2.) Describe the various forms of nebulæ. (May, 1888.)

(3.) State what you know about variable stars. (May, 1888.)

(4.) Describe the changes of spectra which take place, according to the meteoritic hypothesis, in the evolution of a body like the earth from a nebulæ.

(5.) State Lockyer's grouping of celestial bodies according to temperature.

(6.) Discuss the statement that 'the existing distinction between stars, comets, and nebulæ, rests on no physical basis.'

(7.) What causes have been assigned to account for the phenomens of periodic variability of stars?

(8.) What are 'new stars,' and how can their appearance be explained?

(9.) Write an account of Nova Aurigæ.

(10.) What is exactly meant by the 'magnitude' of a star?

(11.) State what you know concerning the distribution of stars and nebulæ.

(12.) How are the motions of stars in the line of sight and across the line of sight determined?

CHAPTER XIII.

THE EARTH AS A COOLING GLOBE.

By J. C. CHRISTIE, F.G.S.

That the earth was once in a molten condition is one of the axioms of modern geology, and that the process of cooling, by which a solid crust was formed upon its surface, is still in operation, is proved by the fact that, wherever the crust is pierced by mines, artesian wells or tunnels, an increase of temperature is invariably experienced. The rise in temperature is continuous, no matter to what depth we descend, but the rate varies greatly in different localities and even in the same boring. This proves that there is a vast storehouse of heat deep below the surface of the earth, and we know by the laws of heat that the warmer layers of the earth's crust below must be continually transmitting by conduction a portion of their heat to the cooler layers above them. That the crust does not thereby ultimately acquire a uniform temperature throughout proves that the transmitted heat is being slowly radiated into space, and unless the source of heat is continually replenished, the ultimate result must be the reduction of the temperature of the entire globe to approximately that of the mean annual temperature of the air in contact with it. But as that varies in different latitudes and areas, the differences will tend to equalize themselves by lateral conduction beneath the surface. Were there no other source of heat than that of the sun, the temperature below the zone affected by the solar heat would be absolutely uniform to the centre of the earth. Such a source of heat was suggested by Sir Humphrey Davy, whose theory of chemical

reactions among the mineral constituents of the interior of the earth was proposed to account for the existence of the internal heat, especially as manifested in the phenomena of volcanic eruptions. The metals of the alkalies (sodium, potassium) and the alkaline earths (calcium, strontium, and barium) were supposed to exist in an unoxidised state in the interior of the earth, and water from the surface, on getting access to them, was supposed to be decomposed, the hydrogen being set free and the oxygen combining with the metals and giving rise to sufficient heat to melt the rocks. Had this been the case, an enormous amount of hydrogen would have been evolved and would have accompanied every volcanic eruption ; such however is not the case, the amount of hydrogen is very small, while the amount of water emitted in the form of steam is enormous.

This theory was also adopted and advocated by Daubeny, but was ultimately abandoned by Davy himself, and is now rejected by all competent geologists as not being in accordance with facts and insufficient to account for them. Another theory much less entitled to consideration was that of Poisson, who tried to account for the underground temperature of the earth by supposing that it was due to our Solar System having passed through a hotter region of space at some remote epoch. More recently a similar attempt has been made to account for the Glacial Epoch by suggesting that it was due to our having passed through a colder region in space. Lord Kelvin has demonstrated the incompatibility of Poisson's theory with the history of life upon the globe by showing, from what is known of the rate of increase of underground temperature, which he estimates at 1°F. in 50 feet, that if this supposed episode had taken place between 1,250 and 5,000 years ago, the temperature of the hotter region of space which was passed through must have been 25° to 50°F. above the present mean temperature of the earth's surface. Neither written nor unwritten history records such a change of temperature, which would have rendered the tropical regions uninhabitable; we have contrary evidence in the fact that 5,000 years ago the distribution of animal and vegetable life upon the globe was practically the same as it is to-day. Had it occurred 20,000 years ago, it must have been 100°F. warmer than now, and if it occurred over 20,000 years ago, it must have been over 100°F., which would have destroyed all animal and all vegetable life (except some of the algæ) within the tropics, and relegated any surviving forms of life to the limits of the Arctic circle. Rejecting then the theories which have been

referred to, we accept in their place that first proposed by Leibnitz, who attributes the rise of underground temperature to the residual heat of a globe which was once in a molten condition.

Lord Kelvin calculates, on the assumption of 10,000°F. being the melting point of rock material, that the consolidation of the earth may have taken place 200,000,000 years ago, but if 7,000°F. (which seems a very high estimate, 4,000°F. being probably nearer the mark or even over it) is the melting point, then it may have taken place 98,000,000 years ago. After making still further allowance for possible sources of error, he sets down the limits at 20,000,000 years as the most recent, and 400,000,000 years as probably the most remote date at which consolidation can have taken place. The limits being so very wide suggests the possibility of the estimates being based upon data which might justify a further extension of the date of consolidation into a still more remote past. Lord Kelvin admits the reasonableness of such a supposition by justifying the adoption of such very wide limits in his calculations. And considering that the calculations of the astronomer and the physicist in regard to problems connected with the earth and its physical condition, past and present, are often based upon imperfect data in which some factor has been overlooked, leading to subsequent correction, we may therefore, while treating them with respect, receive them with a measure of caution due to the fact that the laws of Nature bearing upon the condition of matter under circumstances of which we have no experience and which we cannot investigate experimentally are by no means understood.

Assuming 100,000,000 years ago as the date at which the earth solidified and that it was then, after solidification, at a uniform temperature throughout its mass of 7,000°F. above its present surface temperature, Lord Kelvin arrives, by the aid of Fourier's mathematical theory, at the conclusion that, at the present day, the residue of that original heat should give a rise of 1°F. in every 51 feet of descent down to a depth of 100,000 feet or so. From there down to 400,000 feet it should be 1°F. in 141 feet, and at 800,000 feet it should diminish to 1° in 2,550 feet. From this depth to the centre, he thinks that 'the whole mass, or all except a nucleus cool from the beginning, is (whether liquid or solid) probably at, or very nearly at, the proper melting temperature for the pressure at each depth.' As will be seen later, theory is in accordance with fact in regard to the diminution in the rate of increase as we go downwards, but there are good grounds for

rejecting the assumption of 'a nucleus cool from the beginning' ever having had any existence, and better grounds for believing that the entire globe was once in a liquid condition due to intense heat.

Pursuing the same reasoning and adopting the same data as in the last case, he believes that 10,000 years after the globe began to cool at the surface there would be a rise of 1°F. for every 6 inches downwards near the surface and that it would go on diminishing at a rate inversely proportional to the square roots of the number of years from the commencement of solidification. Thus after 40,000 years the rate of rise would be 1° for every foot, after 160,000 years 1° for every 2 feet, after 4,000,000 years 1° for every 10 feet, and after 100,000,000 years it would be 1° for every 50 feet. He therefore thinks it probable that the rate of increase has, during the last 96,000,000 years, gradually decreased from 1° in 10 feet to 1° in about 50 feet, and that the thickness of the crust has increased during the same period to 5 times what it was at the commencement of it. This shows that the rate of increase of temperature downwards was probably much more rapid in the earlier stages of the earth's history than at the present time, which is equivalent to saying that it cooled more rapidly then than now.

The Rise in Underground Temperature.—The fact that a rise of temperature is experienced when we descend to considerable depths below the surface was recorded as far back as 1740 by Gensanne, who made observations in the mines of Giromagny, and by d'Aubuisson, who in 1802 made others in the mines near Freiberg. In our own country Mr. Lean, in 1815, published the results of similar observations in Wheal Abraham mine, Cornwall, and Mr. Bald, in 1819, on mines in Cumberland. The indications afforded by artesian wells and by borings for coal mines, as well as those from heated and boiling springs, subterranean tunnels and volcanic eruptions, all point to the existence of a source of internal heat that is not confined to any particular area under the earth's surface, but is widely, and quite evidently everywhere, distributed over the entire area of the globe, which forbids the supposition that the source of heat is in any sense local. The rise does not, however, commence just below the surface, it commences at a point which is determined by the depth to which the solar heat, with its diurnal and annual variations, penetrates, and this depends upon the latitude of the place, the mean annual temperature of the air as affected by the prevalent

winds and ocean currents, and the varying conductive powers of the different rocks and soils. The annual variations slowly penetrate downwards in succession, an abnormally cold winter increasing the depth to which they are felt, and an abnormally warm summer diminishing it; when the average limit of variation is reached an approximately invariable temperature prevails all the year round and from year to year. This constancy is well exemplified in some caves; *e.g.*, in the Mammoth Cave, Kentucky, where, although the surface temperature varies greatly with the seasons, an equable temperature prevails all the year round. At one time this was supposed to be likely to conduce to the cure of consumptive patients, for whom houses were built in its long and lofty passages; but the hopes entertained of its beneficial effects were not realised. This limiting boundary constitutes, as it were (to borrow a political phrase) the frontier between 'the sphere of influence' of the internal heat of the earth and that of the sun. Owing to the causes already mentioned, its depth varies from 2 or 3 feet as in Java, to 50, 60, or even 80 feet in temperate climes, and 700 feet where the soil is said to be permanently frozen at Yakutsk in Siberia.

This boundary constitutes an irregular surface whose contours do not correspond exactly with those of the surface of the earth, for they do not rise under mountain ranges proportionately to the rise of the surface above them, nor do they sink proportionately below the curves of deep valleys and gorges. The exceedingly low temperature of the water, even as low as 27·75° F., at the bottom of the deep oceans, must be another cause of unconformity between the two surfaces, for its refrigerating effect must penetrate to a much greater depth into the earth's crust than the effect of the temperature of the air within temperate climes, not to speak of the tropical regions.

Everywhere beneath the depth of constant temperature, a rise is experienced, but the rate varies greatly in different localities and also at different depths in the same vertical descent. The rate is often somewhat capricious, maintaining the average rate in any given boring for a considerable depth, then diminishing, that is a greater distance requiring to be descended in order to experience a rise of 1°, and then resuming the average amount of descent for a rise of 1° in the temperature.

These seemingly capricious variations are accounted for by the difference in the conductive power of the rocks traversed by the

boring, by the influence of underground springs of heated water rising towards the surface, or of cold springs descending, whose contiguous presence is thus felt, though unseen, and by residual heat from intrusive sheets or masses of igneous rocks.

The Evidence from Mines.—Though mines would at first sight appear to offer an easy and perfect means of ascertaining underground temperature, there are many sources of error which require to be considered and guarded against. The temperature of the air would be misleading. In addition to the heat given off by the men (and horses in the case of coal mines) and the use of lamps and explosives, there is the heat developed in the compressing of the air by the increase of the atmospheric pressure above it, when it has descended from the surface to ventilate the mine at great depths. Nor can the water encountered at different depths in mines be depended upon, for unless it has percolated through the rock for a considerable distance in a horizontal direction at the depth at which it is tapped, it will be colder than it ought to be if it is descending and warmer if it is ascending. Thus d'Aubuisson in 1802 found at the bottom of the Himmelfahrt mine, 820 feet deep, that the temperature of the water, which had penetrated from above, was only 58·46°, while that of the air was 59°. On the other hand, in the Kühschacht mine, 394 feet deep, which had been flooded by an influx of ascending water, the temperature of the water was 61·34°, while the air was only 59°. It is the temperature of the rock that must be observed. To obtain accuracy, a newly uncovered rock-face that has been laid bare by mining should be pierced in a horizontal direction by boreholes about 2 feet deep, and after time has been allowed for the dissipation of the heat generated by the boring of the holes, the thermometer should be inserted, bulb first, and the hole plugged with sand, and after the mercury has become stationary, the reading should be taken. From this the annual average temperature of the locality is subtracted and the depth to which it penetrates, that is the depth of invariable temperature, is subtracted from the depth at which the reading is taken and with these data the rate of rise per foot of descent is calculated, or the number of feet of descent necessary for a rise of 1° of temperature.

The better to impress upon the mind the fact of the variation in the rate of the rise in underground temperature and the limits of these variations, a number of the data are given of the observations made in metalliferous mines, coal mines, artesian wells,

and railway tunnels which have pierced mountain masses at considerable depths beneath the surface. The rate of this rise of temperature is indicated by the number of feet mentioned, thus 64 feet means a rise of 1° F. for every 64 feet of descent, or a rise of $\frac{1}{64}$ of a degree for every foot. Another way of expressing this fact has been adopted in those countries where the Metric System is in use, the vertical distance in metres between any two points whose temperatures differ to the extent of 1° C. is called a Geothermal Degree. But as most unfortunately Britain has not yet seen fit to adopt this system, the following data will be given in feet and degrees Fahrenheit, and the Geothermal Degree, which will be represented by the abbreviation G.D., will be expressed in these terms, thus G.D. of 60 feet will indicate a rise of 1° F. for every 60 feet, or $\frac{1}{60}$° F. per foot. A radius of the earth is thus considered as the tube of a gigantic thermometer, which is graduated from the top downwards at irregular intervals, and whose bulb is at the centre. The degree, however, is expressed in feet and not in degrees of heat, and in this way the rate of rise is conveniently indicated.

Metalliferous Mines have afforded examples of extreme variations, from a G.D. of 29 feet in Cornwall to 215 feet in Saxony. D'Aubuisson recorded an average G.D. of 58 feet in Saxon mines, and 39 feet at Poullaouen. Lean at Wheal Abraham recorded, in descending order, 48, 59, 84, and 29 feet at various depths in the same mine, average G.D. = 55 feet. De Lapparent considers this as nearly the average for Europe, but other Cornish mines gave 40, 43, and 49 feet. Reich made a series of observations in the mines of Saxony, which he conducted with the greatest care, every precaution then known being taken in order to ensure accuracy. Thermometers with large cylindrical bulbs and long but very narrow tubes were used, with which it was possible to take readings to $\frac{1}{50}$° F., and they were placed in such positions as were least likely to lead to their being affected by the air or by heat generated in the working of the mine. His observations extended over a period of 18 months in the years 1829—30 and 31, during which he took no less than 12,936 readings, and obtained an average G.D. of 76 feet. More recent observations in Saxon mines have yielded very different results, varying from 29 feet to 215 feet, the average being a G.D. of 101 feet. A mine in Ireland gave 56·5 feet, one in Scotland 114·83 feet, and two in the Urals gave 42 and 47 feet respectively. Henwood, whose observations were extended to

America, recorded 34 feet in Cornwall and 156 feet in Minas Geraes in Brazil, and Schwarz, from more recent observations in the Schemnitz mines in Hungary, recorded 75 feet. Cordier found that the rate varies in different mines as 1 to 3 and that a still greater difference is observable when the extremes of one mine are contrasted with those of another, the variation then amounting to as much as 1 to 7. Fox has noted a most interesting fact in connection with the temperature of metallic veins when contrasted with that of the rock in which they occur. He found that, at the same depth, the former is sometimes warmer than the latter by as much as from 1·8° to 4·84°, the vein stuff being a much better conductor of heat on account of its metallic nature and homogeneity. The fact that it often occurs as layers lining the walls of the fissures, also facilitates the conduction of the heat which passes more freely within a layer or bed than from one layer to another. Metallic veins generally occur in an approximately vertical position in the rocks in which they have been formed, the fissures taking an upward direction. The average of these observations gives a G.D. of 64 feet if we include the exceptional one of 215 feet, excluding it we get 50 feet only.

Coal Mines give a smaller geothermic degree than metallic mines, the rise of temperature being at a more rapid rate as we descend. This is readily to be accounted for by the fact just mentioned that heat passes less freely from layer to layer, that is across the bedding of rocks, than it does in passing in the direction of stratification, and the same holds true of the crystalline schists, for heat passes more freely in the direction of their foliation than across it. This retards the upward passage of the heat and diminishes the vertical distance between any two points whose temperatures differ to the extent of 1°, hence we say there is a diminution in the geothermal degree, which however is equivalent to saying that there is a rise in the rate at which temperature increases downwards. Among the results obtained from observations in coal mines are the following: in the mines of Cumberland, Durham, and Northumberland, Bald obtained in different mines a G.D. of 28, 36, 41, 43, and 47 feet; Phillips at Newcastle, 60 feet; Hodgkinson at Manchester, 71 feet, and Fox, 74 feet. More recent data have been obtained in the Rose Bridge colliery at Wigan, which has been sunk to the great depth of 2,445 feet, where a temperature of 94° was observed. The annual average temperature of the air at the surface in this locality is about 49°, and if this temperature penetrates the crust to, say, a depth of 45 feet

and remains constant there, this would give a G.D. of 53 feet; but supposing it penetrates to, say, 100 feet, which is certainly the maximum depth possible, it would only diminish it to 52 feet. The rate of rise in this shaft is far from uniform, for at various depths in descending the G.D. is 57·7 feet, 48·2 feet, 33 feet, and in the deepest portion of the shaft 54 feet. The differences in the nature of the rocks pierced by this deep shaft will account for some of the variation to which the influence of currents of water in the neighbourhood of the shaft may also contribute. The rocks in the coal measures are very varied in their character, consisting of coal seams alternating with beds of fire-clay, shale, sandstone, and limestone. With such variations occurring in a single pit, the variations between different mines need occasion no surprise—for example, 49, 38, 28, and 28 feet observed in 4 pits respectively by Marsilly at Anzin; 62 feet by Houzeau in the Belgian coal-field; 28 feet at Decize, and 35 feet at Littry, by Cordier. The average of these seven Belgian and French mines is 38 feet, and of nine English mines is 50·78 feet.

Artesian Wells.—The bore-holes for these wells and those made in the search for coal have been largely utilized for making observations on underground temperature, and have contributed greatly to our knowledge of it. As they often become filled with water before their maximum depth is attained, and as, of course, the actual depth from which this water comes is unknown, seeing that it may be an ascending or a descending current and not belonging to the rock at the depth at which it is tapped, and as convection currents would tend to equalize the temperature of the entire column of water, precautions must be taken to neutralize these sources of error. This is done by passing a rod through two discs of india-rubber and fixing them at a sufficient distance apart so that a thermometer can be attached to it between them. The discs are of sufficient diameter to fit the bore-hole tightly like a piston, and when the rod on which they are fixed is lowered into the bore-hole to the required depth, they isolate a portion of the column of water and prevent colder or warmer water from mixing with it until sufficient time has elapsed to allow it to acquire the temperature of the rock with which this portion of the column is in contact. Thermometers adapted and used for this purpose are called geothermometers. As is the case in mines, the variations in the Geothermal Degree in artesian wells are considerable. At La Rochelle it is 1° for 36·83 feet; at Pitzbühl, near Magdeburg, 48·3 feet; at Neusalzwerk, Westfalen, 53·22 feet; at Rudersdorf,

near Berlin, 54·68 feet; at Mouillelonge, Creusot, 55·95 feet; at Torcy, Creusot, 55·95 feet; at St. Andre, Eure, 56·41 feet; at Mondorf, Luxemburg, 56·39 feet, and at Antern, Thuringen, 72·9 feet. The average of these nine wells is 54·51 feet. At Grenelle, Paris, in a well 1,797 feet deep, with a bottom temperature of 81·86°, it is 58 feet, but the rate varies in different parts of the boring, giving as the G.D. at five successive points, in descending order, 47, 41, 120, 71, and 66 feet. Again La Chapelle, another of the great artesian wells of Paris, 2,165 feet deep, where the temperature is 76°, gives the much higher G.D. of 86·3 feet for the entire depth, but with variations in descending order of 36, 142, 88, 93, 91, 136, and 196 feet. The great discrepancy between these two wells at Paris, which are approximately of similar depth and give respectively 58 and 86·3 feet, is equalled by two others at Naples, which are only a mile apart; the one, 909 feet deep, gives a G.D. of 83 feet, the other, 1,460 feet deep, gives G.D. of 208 feet. A probable explanation of the great diminution in the rate of increase of temperature in the latter may be the possibility of sea-water having percolated through the rock in which the bottom of the well is situated. This is the only explanation which will satisfactorily account for a fall instead of a rise in temperature in a boring 200 feet deep at Bahia, South America. An anomaly in the opposite direction is afforded by the well at Neuffen, Wurtemberg, which gives only 19 feet, but this is accounted for by its proximity to igneous rock of comparatively recent date. A trial boring, made in searching for coal in 1843 at Monte Massi in Tuscany, to the depth of 1,141 feet, gave a G.D. of 23·69 feet, but this also is accounted for by the presence in its immediate neighbourhood of salses and hot springs, the residual effects of recent volcanic activity. The deepest boring of all hitherto made is the one at Sperenberg, 25 miles south of Berlin. After traversing the soil and the alluvial deposits, it passes into a deposit of rock salt of great thickness, in which it attains a depth of 4,163 feet, where a temperature of 118·5° was observed. The mean annual temperature of the air at the surface is 49·5, and as this penetrates to a depth of about 72 feet, there is a rise of 99·03° in 4,091 feet or a G.D. of 59·2 feet for the whole depth of the shaft. But the rate varies greatly at different depths. At nine different stations, beginning at a depth of 721 feet, in descending order, the G.D. was found to be 61, 39, 255, 52, 62, 52, 42, 69, and 241 feet. The average G.D. for this lower and larger portion of the boring (3,442 feet) is 97 feet. The two remarkable increases in the

geothermal degree, that is, decreases in the rate of rise in the temperature, of 255 and 241, occur respectively at about one-third of the way down and at the bottom. The contrast between the G.D. for the whole boring, viz., 59·2 feet, and that of the lower portion, viz., 97 feet, shows very clearly, as is also the case at Grenelle and La Chapelle, that though there is a continuous increase in temperature as we go downwards, there is also a diminution in the rate of that increase. The bearing of this fact on the general question of underground temperature will be seen further on.

Mountain tunnels have also contributed some important data in regard to this question, especially those which have, in the construction of the European international railways, pierced the masses of Mont Cenis and the St. Gotthard at greater depths beneath the surface than any vertical boring has yet attained.

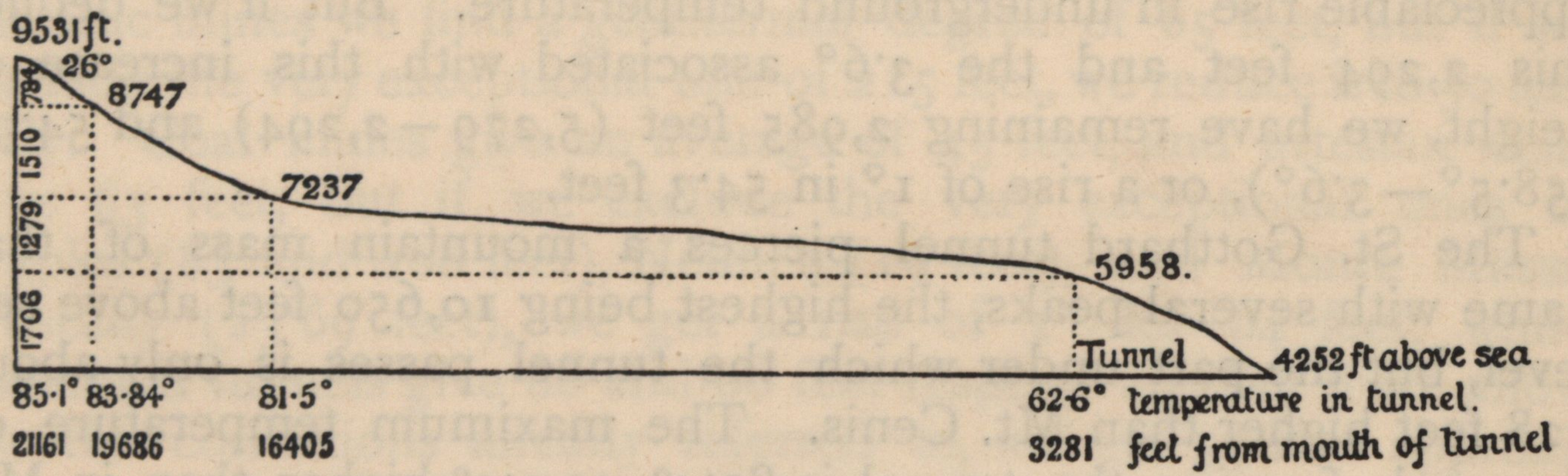


Fig. 97.

The summit of Mont Cenis is 9,531 feet above sea level, and the tunnel, which is the highest point in the railway, passes under it at a height of 4,252 feet or 5,279 feet (just one foot less than a mile) beneath the surface. At this point, which is a little over four miles from the southern end, the temperature of the rock is 85·1°. The temperature at the summit is approximately 26·6°, therefore there is a rise of 58·5° in 5,279 feet or a G.D. of 1° in 90·23 feet. Entering the tunnel at its southern end and passing inwards to a point 3,281 feet from the mouth, we find a temperature of 62·6°, and that the surface has, as it were, risen to a height of 1,706 feet above the level of the tunnel. At 16,405 feet from the mouth and 2,985 feet below the surface, we find 81·5°; at 19,686 feet from the mouth and 4,495 feet below the surface, we find 83·84°; at 21,161 feet (just over four miles) from the mouth and 5,279 feet below the summit, we find 85·1°. From these data the

striking fact is learned that the rise of the surface from 2,985 to 4,495 feet (*i.e.*, 1,510) above the level of the tunnel is accompanied by a rise of only 2·34°, and a further rise from 4,495 to 5,279 feet (*i.e.*, 784) is accompanied by a rise of only 1·26° in the temperature of the rock in the tunnel. Now the point in the tunnel where 81·5° is observed is vertically 2,985 feet under the surface, which here is 7,237 feet above sea level, or closely approaching the limit of perpetual snow. Where the temperature of 85·1° is observed, it is 5,279 feet below the surface, that is, the summit of the mountain, which is 9,531 feet above the sea level. From this we ascertain that a rise of 2,294 feet in the height of the mountain above the level of the tunnel is accompanied by a rise of only 3·6° in the underground temperature, or a rise of 1° in about 637 feet. Hence it appears that when we penetrate beneath lofty mountain masses, any increase in their height above that which reaches or approaches the limit of perpetual snow is not accompanied by any appreciable rise in underground temperature. But if we deduct this 2,294 feet and the 3·6° associated with this increase of height, we have remaining 2,985 feet (5,279 − 2,294) and 54·9° (58·5° − 3·6°), or a rise of 1° in 54·3 feet.

The St. Gotthard tunnel pierces a mountain mass of that name with several peaks, the highest being 10,650 feet above sea level, but the part under which the tunnel passes is only about 328 feet higher than Mt. Cenis. The maximum temperature of the rock forming the tunnel is 87·4°, or 2·3° higher than in Mt. Cenis, so that the rise in temperature for this increase in height is only at the rate of 1° for 142 feet. For the whole distance between surface and tunnel the G.D. is 88 feet, but if we make the same deductions in regard to the upper part of the mountain as in Mt. Cenis, we shall reduce it to about the same, viz., about $54\frac{1}{2}$ feet. The observations at the St. Gotthard have shown that under escarpments there is a great increase in the geothermal degree; under one of them it rises to 113 feet, showing that there is a great loss of heat in a lateral direction, the face of the escarpment being nearer to the area affected than the surface is. Nor must it be forgotten that, as in mines and borings, the temperature of the rock in tunnels will be influenced by the nature of the rock, for rocks vary considerably as conductors, and by the joints and faults by which they are traversed, which permit currents of water of different temperatures to raise or lower that of the rocks according to circumstances. The observations in mountain tunnels have also demonstrated that the depth at which constant

temperature prevails does not rise under mountain masses proportionally to the rise of the surface, and hence does not correspond to its contours, but assumes an approximation to a horizontal plane. In fact, so great is the loss of heat, both vertically by the summit and laterally by the steep slopes of high mountain masses, that their influence may be almost ignored in calculations. Another important fact was disclosed in the St. Gotthard tunnel. In the centre, the temperature of the air is 95°, which is the highest temperature that Europeans can endure with safety in a moist atmosphere even when not engaged in violent labour. Should any attempt be made to carry out the projected tunnel under Mt. Blanc, provision will require to be made for not only cooling but drying the air while the tunnel is being bored, for the temperature observed in the St. Gotthard indicates that 122° or more is likely to be encountered under the summit of Mt. Blanc.

On comparing the results of the observations recorded in metallic mines we find a geothermal degree of 65 feet, but if we exclude the very exceptional one of 215 feet, we reduce it to 50 feet only. Coal mines give an average of 45 feet, and artesian wells give 63 feet, but if we exclude the very exceptional ones of Naples (83 and 208 feet), Neuffen (19 feet), and Monte Massi, Tuscany (23·69 feet), we get a rise of 1° for 64 feet, while mountain tunnels give 88 and 90 feet respectively, but if we allow for the corrections already referred to, we get 54 feet approximately in both Mt. Cenis and the St. Gotthard. That the geothermal degree should be lowest in coal mines is accounted for by the difficulty with which heat passes from bed to bed of rock in a series consisting of rocks of different kinds; that it should be higher in artesian wells may be due to the facts that the rocks traversed differ less from one another than is the case in coal strata, and that the presence of the water in the rocks tends to increase their conducting power; and that it should be highest in metallic mines may in part be accounted for by the greater conductivity of the more homogeneous rocks in which they occur, and partly by the fact that, as a rule, the mouths of artesian wells and coal mines are not much above sea level, while those of metallic mines are generally in mountainous districts, and hence at a greater distance from the source of internal heat, consequently the surfaces of equal temperature (geoisotherms) approach nearer to each other in the former than in the latter, that is, the G.D. is smaller which is equivalent to a more rapid rate of rise in the underground temperature. The irregularity in the rate of increase

gave rise to much controversy, and when the results of the observations (made at a cost of £8,800 by the Prussian Government) at Sperenberg were announced, the fact that they indicated a tendency to a diminution in the rate of increase was seized upon as evidence of the unsoundness of the theory of the internal heat of the earth. Carl Vogt protested that such results could not be possible if the idea of an internal source of heat was correct, and asked if it is consistent with common sense to expect that, when approaching a source of heat, it should be necessary to traverse a greater distance to obtain a given rise in temperature the nearer the source of heat is approached, and illustrated his meaning by asking if, in bringing his finger nearer to a lighted candle, the rate of increase of heat would become slower and slower the nearer his finger approached it. Mohr, in his 'History of the Earth,' considered that the Sperenberg boring had 'cruelly annihilated' the theory of the internal heat. But it must be borne in mind that, though the rate of increase showed such altogether exceptional variations, there is a continuous increase of temperature in it as in all others (Bahia excepted), and though the anomalies are very striking and their causes have not been actually demonstrated by proof, we must in the end rely upon the average result derived from the entire series of observations. As regards Vogt's comparison of an artesian boring to the approach of his finger to a candle flame, he was in error both in his reasoning and his facts. Though the rate of increase diminishes the nearer we approach the source of heat, still there is a continuous increase in the boring as in the approach of the finger to the flame. That the rate of increase in the boring should diminish is due to the difference between the two media through which the heat is transmitted under an entirely different set of conditions. The internal heat of the earth is not like that of a candle or fire whose heat is not diminished in the lapse of time because the heat is constantly renewed by the addition of fuel. Every heated body whose heat is not being renewed by combustion parts with its heat by conduction to surrounding space and tends to equalize its temperature throughout, and it is only where it comes in contact with a cooling medium (*e.g.*, the atmosphere) that a rapid exchange of temperature takes place between the two, causing the surface of the cooling body to lose its heat more rapidly than the interior; hence the surfaces of equal temperature within the cooling body are nearer to each other near the surface, and become more widely separated the nearer

they approach the centre. This is exactly equivalent to a rise in the geothermal degree, so that what Vogt and Mohr and their followers regarded as evidence destructive to the theory of the internal heat of the earth having its source at the centre, is rather the strongest of evidence in favour of it. The researches and reasoning of Fourier, Poisson, and Elie de Beaumont, leave no doubt on this point, and the experiments of Bischof confirm the correctness of the theory. He fused some basalt, and had it cast in the form of a sphere 29½ inches (·75 metre) in diameter. He made provision for the insertion of thermometers by leaving cylindrical holes in it which ran from the surface towards the centre, and, after the mass had been allowed to cool for 48 hours, observed the temperature at different depths. The sphere was ·75 metre or 29·52 inches in diameter, the radius therefore was 14·76 inches. The temperature of the surrounding air was 68°, and when he made his first observation in a hole 5·139 inches below the surface, he found 278° or a rise of 210° in that distance, which gives a G.D. of ·02447142 inches. His second observation was made at a depth of 7·480 inches, where he found 312·8°, or a rise of 34·8° in 2·341 inches, which gives a G.D. of ·06727011 inches. His third was made at a depth of 10·275 inches, where he found 338°, a rise of 25·2° in 2·795 inches, or a G.D. of ·11091269 inches. His fourth was made at 14·764 inches, where he found 377·6°, a rise of 39·6° in 4·489 inches, or a G.D. of ·11361111 inches. From this it is seen that there is a considerable rise in the G.D. as the centre is approached, the second being nearly treble that of the first, about 11 to 4; the third being about one-half more than the second, about 13 to 8; and the fourth slightly in excess of the third, which shows that there is a decided decrease in the rate of rise of temperature in a cooling body as the internal source of heat is approached.

From experiments made by Perry and Ayrton on the thermal conductivity of rocks, they have concluded that a heated sphere of rock such as the earth will cool in the manner represented by Fig. 98, in which temperature is represented by the vertical line OP, time by the horizontal line OX, and the corres-

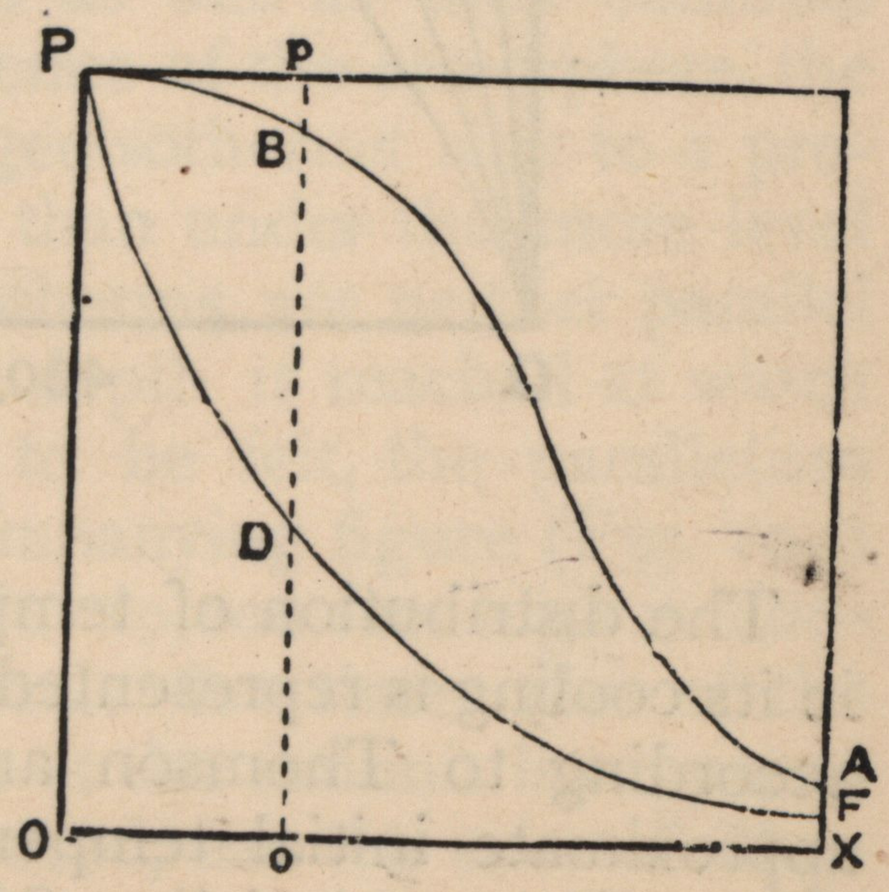


Fig. 98.

ponding excess of the temperature over that of the surrounding medium is represented by ordinates as *op*, parallel to OP, the progress of cooling at the centre by the curve PA, while PF represents cooling at the circumference. The cooling of such a ball will be very different at different places. If very hot, it will cool very rapidly at first near the surface, and then more and more slowly. At the centre it will cool slowly for some time, then more rapidly until it approaches the rate that prevails near the surface. Intermediate places cool more slowly at the beginning, as they are nearer the centre, then ultimately faster than places at the circumference. The amount of cooling which has already taken place in the earth may be represented by the parts PB and PD (of the two curves PA and PF) which lie between OP and *op*; thus at the end of the time represented by O*o*, the excess at the centre is *o*B, that of the surface by *o*D, and the difference BD continues to diminish until the curves PA and PF ultimately meet on the line of the abscissæ OX.

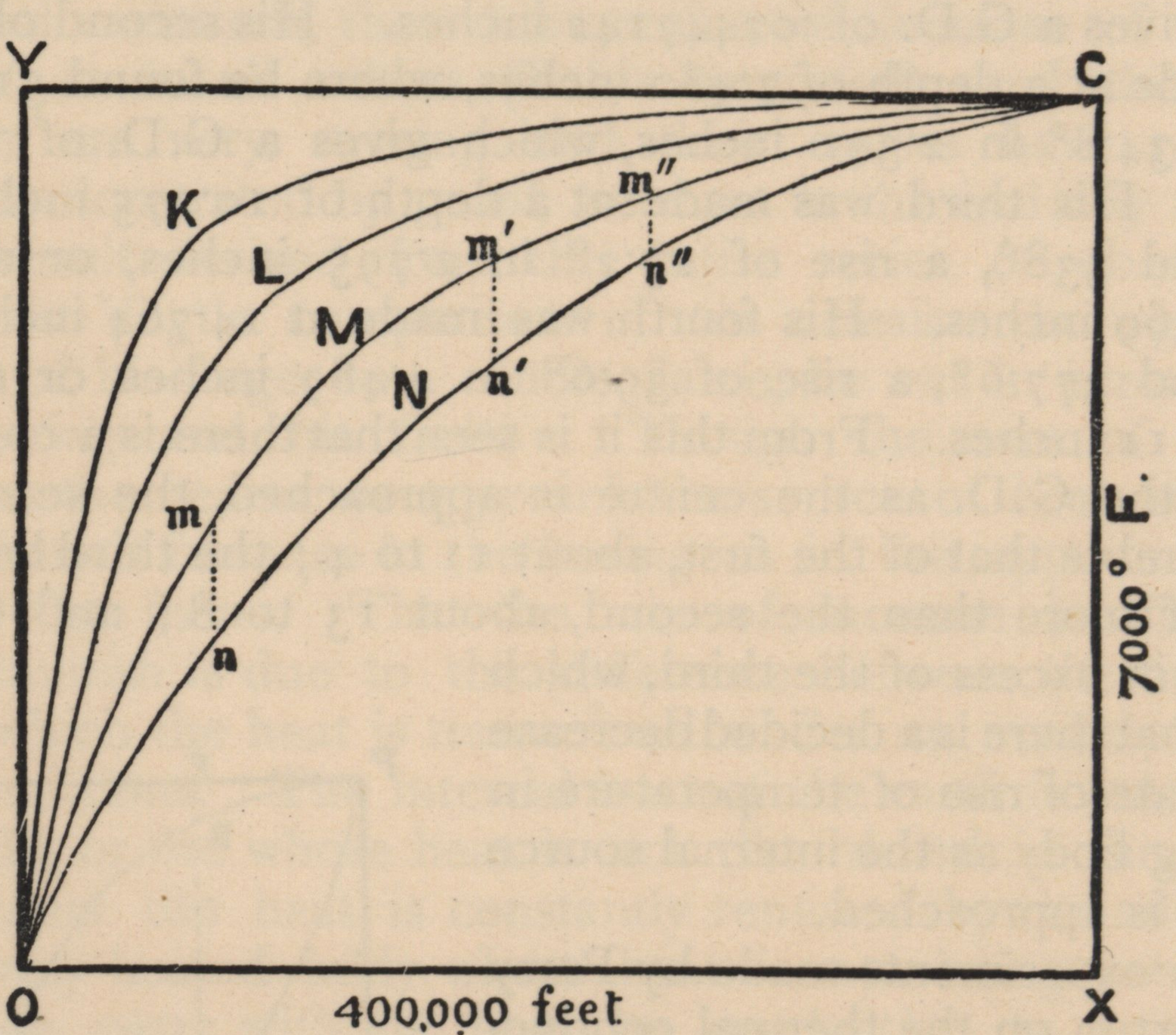


Fig. 99.

The distribution of temperature in the earth at different stages in its cooling is represented in the accompanying diagram (Fig. 99), according to Thomson and Tait, who assume that it had an approximate initial temperature of 7000° before commencing to cool. The vertical line OY represents temperature, depths below

the surface O towards the centre X are represented on OX, and the curve OMC will represent the state of temperature along a radius of the earth one hundred million years after the commencement of cooling, while ONC will represent the condition that will prevail ten thousand years later. The curves OK and OL show approximately the supposed distribution of temperature previous to the time to which the curve OMC applies. The loss of temperature in ten thousand years at a depth of, say, 100,000 feet is represented by *mn*, at 400,000 feet by m^1n^1, at 600,000 feet by $m^{11}n^{11}$. From this it seems to appear that down to a depth of 100,000 feet the temperature increases approximately to the depth, and that after, say, ten thousand years, below a depth of 400,000 feet it will increase directly according to the depth. It also appears that there is a spherical layer in which the loss of heat is greatest, which is gradually travelling nearer and nearer to the centre of the earth. At the present time the loss of heat is proportional to depth down to 200,000 feet, but at the centre it is possibly as hot as it was one hundred millions of years ago. The amount of heat which the earth loses every year by radiation into space is, according to the calculations of Milne, sufficient to raise a layer of water, $\frac{1}{40000}$ inch thick, covering the entire surface of the globe, from freezing to boiling point.

Geoisotherms.—The variations in the geothermal degree demonstrate that, like the zone of constant temperature, the zones of equal underground temperature, which have been termed isogeotherms, but more recently, and also more correctly, geoisotherms, lie at different depths beneath the surface at different places, and are consequently not parallel to its contour lines. In the case of mountain masses, owing to their sides as well as their summits being exposed to the refrigerating influence of the atmosphere, the zone of constant temperature and the geoisotherms sink to a proportionately greater depth within them than under the more level surface of the ground, hence the geoisotherms are neither parallel to the surface nor to each other until a depth is reached at which the irregularities of the surface cease to be felt, the parallelism increasing with the depth. The accompanying figure (Fig. 100) will help to illustrate this. A mountain 10,000 feet high is conventionally represented on a vertical scale five times that of the horizontal. The temperature of the air at the summit is supposed to be 25°, at the base 55°; it is supposed, for the sake of illustration, to decrease with the ascent at the rate of $3\frac{1}{2}$° per 1,000

feet for the first 4,000 feet, 3° per 1,000 feet for the second 4,000 feet, and 2° per 1,000 feet for the remaining 2,000 feet at the top. The temperature within the mountain increases as we descend at a more rapid rate than the air surrounding its surface at the same level, and it is here assumed that at a height of 9,000 feet within the mountain the temperature is 29°, while the air is only 27° at this height. This geoisotherm of 29°, as it passes from the centre to the sides of the mountain, is deflected downwards, and reaches

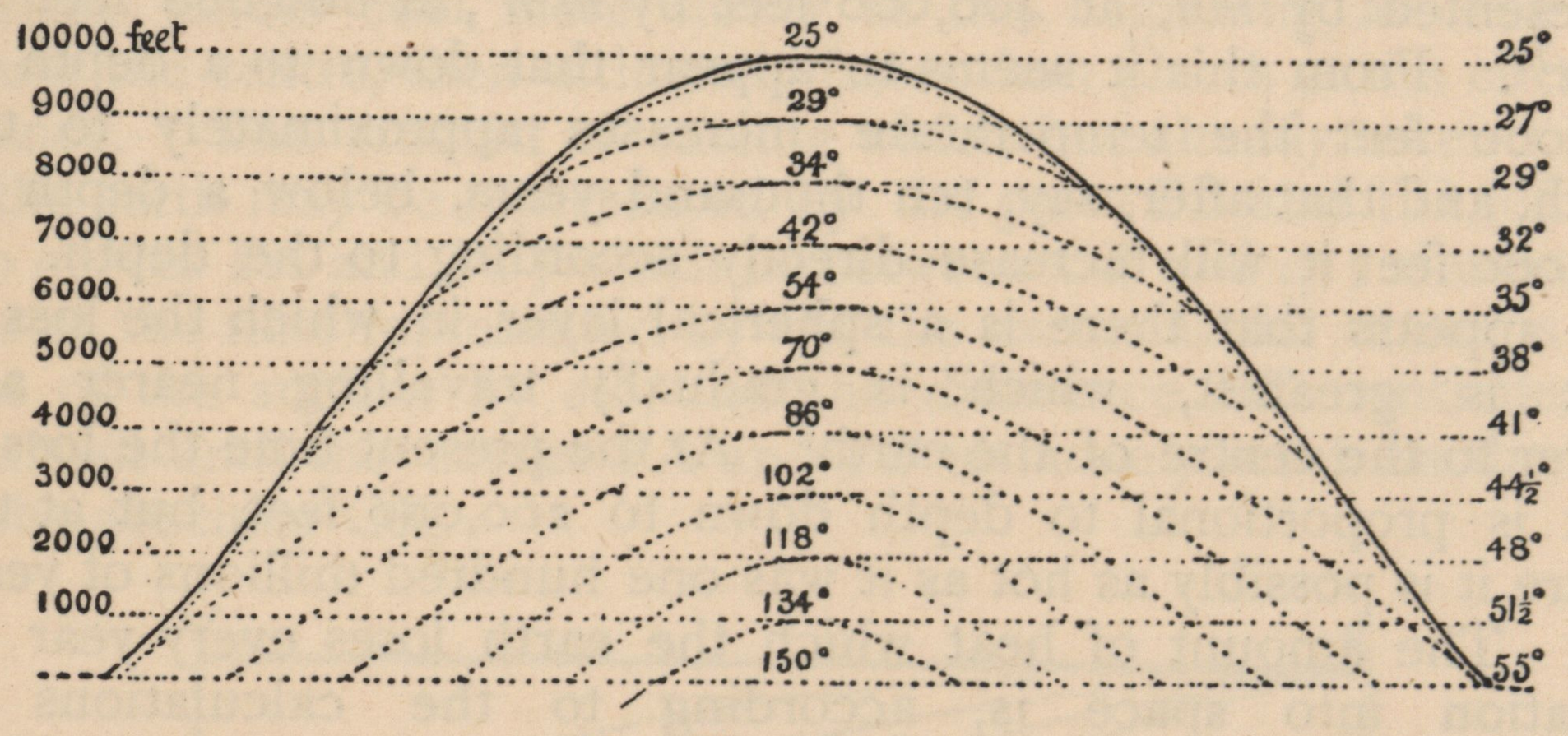


Fig. 100.

the surface at 8,000 feet, 1,000 feet lower than at the centre. In the same way the geoisotherm of 34° is reached at a height of 8,000 feet, but is deflected downwards as it passes towards the sides of the mountain, which it reaches nearly 2,000 feet lower. Again we have 42° at 7,000 feet in the centre, and rather below 4,000 feet at the sides. At 6,000 feet in the centre we have 54°, which is deflected downwards at the sides and passes outwards beneath the surface of the country surrounding the mountain.

In the case of a mountain or range, say 10,000 feet high, being situated near an ocean as many feet in depth, we have a more pronounced accentuation of the fact that different points in a geoisotherm are at different distances from the centre of the earth, a corollary to which is that a different temperature prevails in such cases at the same distance from the centre. Thus in Fig. 101 we have 55° at sea level, but 150° at the same level under the summit of the mountain. Again, at the bottom of the ocean we have 32° and 310° at the same level under the mountain, at 10,000 feet below the bed of the ocean we have only 190°, but 470° at the same level under the mountain, or a difference of 280° at the same distance from the centre of the earth.

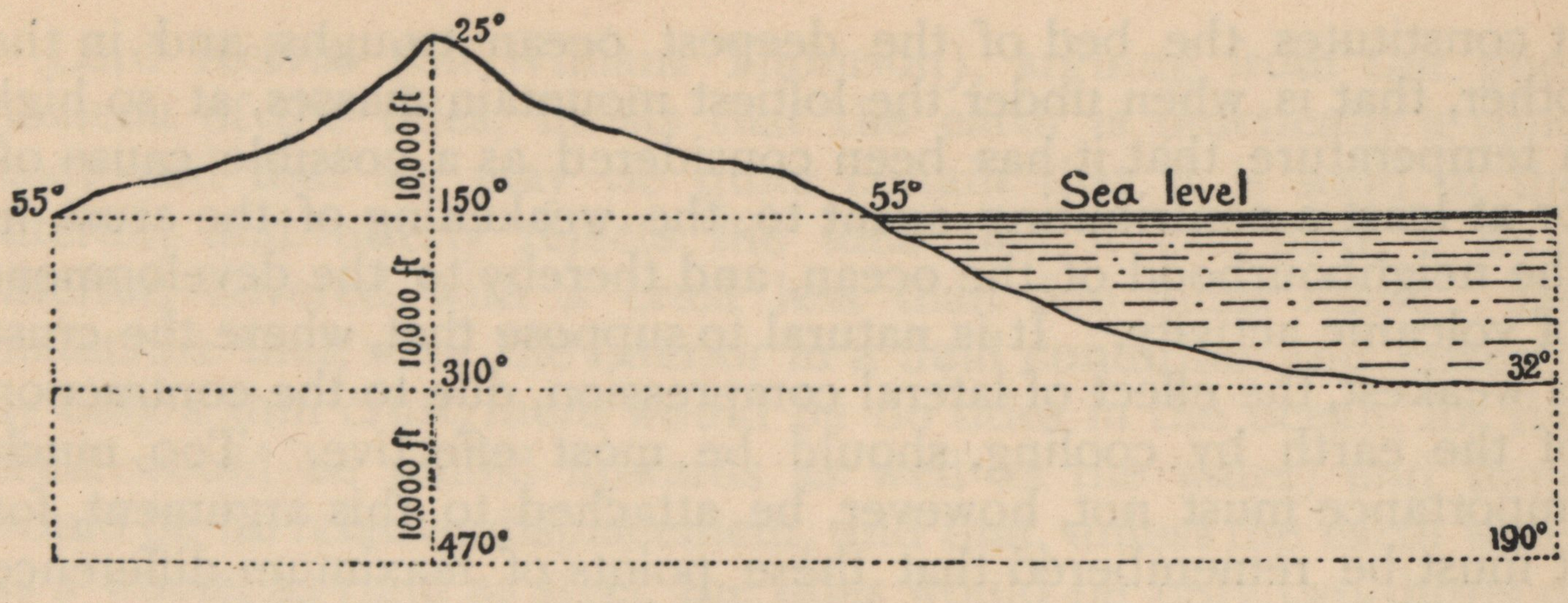


Fig. 101.

In Fig. 102 is represented, on a highly exaggerated vertical scale, a section of a lofty mountain chain and a deep ocean trough, on which the approximate curvature of the geoisotherms is indicated by dotted lines. It will be observed that they are wider apart on a vertical line under the summit of the mountain, and closer together under the trough of the ocean, the consequence of which is that at a certain depth they ultimately become parallel and horizontal. Where this difference of temperature between two points equidistant from the centre attains the maximum amount possible, we have rock in the one case at about 27°, that is when

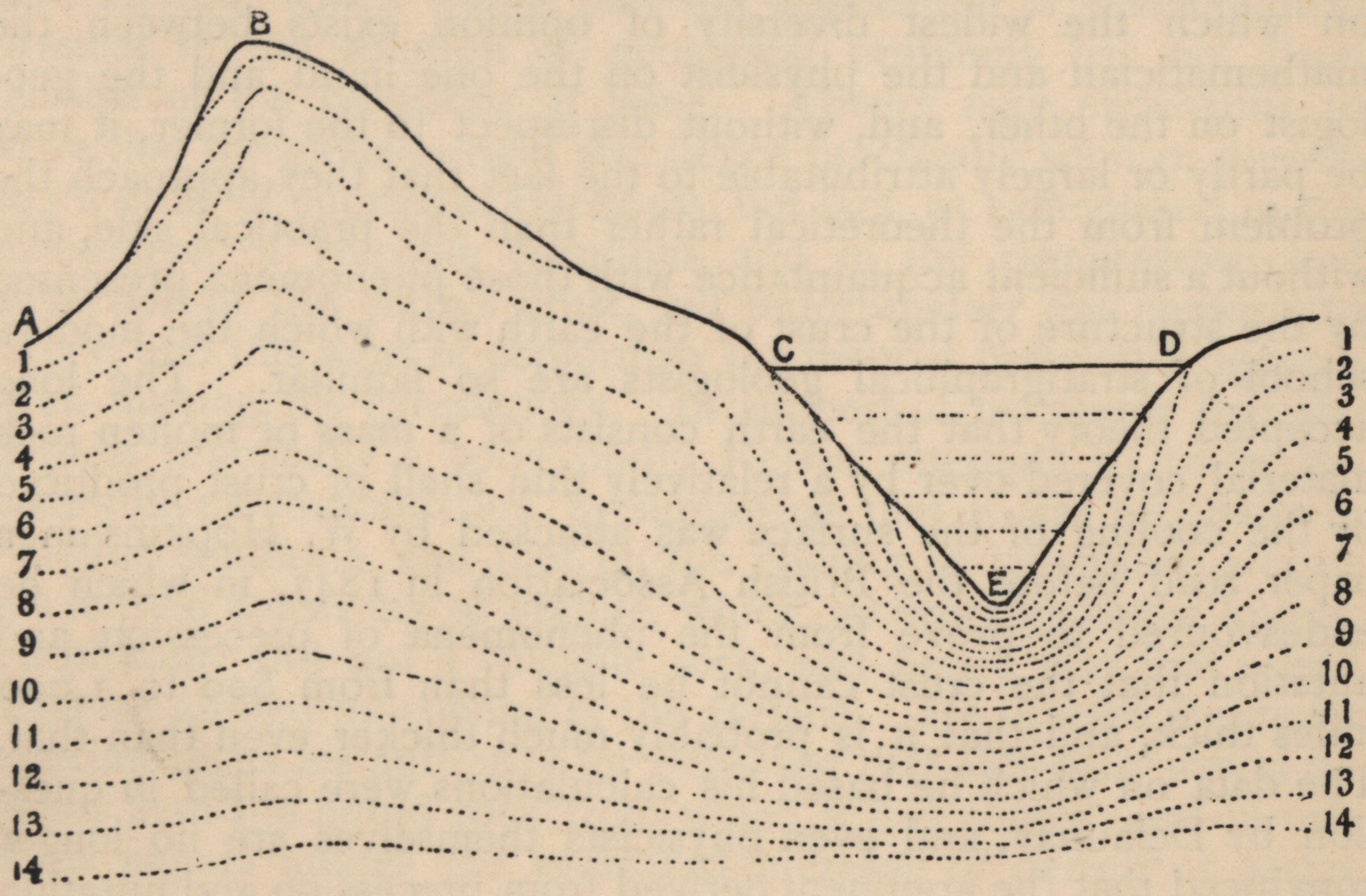


Fig. 102.

it constitutes the bed of the deepest ocean troughs, and in the other, that is when under the loftiest mountain masses, at so high a temperature that it has been considered as a possible cause of, or at least a contributing agent to, the weakening of the crust in the neighbourhood of the ocean, and thereby to the development of volcanic activity. It is natural to suppose that, where the crust is weakest, the effect of lateral compression, due to the contraction of the earth by cooling, should be most effective. Too much importance must not, however, be attached to this argument, for it must be remembered that these points of maximum difference are widely apart, and consequently the transition of temperature between them must be gradual.

CHAPTER XIV.

THE INTERIOR OF THE EARTH.

The Condition of the Interior of the Earth is a subject on which the widest diversity of opinion exists between the mathematician and the physicist on the one hand and the geologist on the other, and, without disrespect to the former, it may be partly or largely attributable to the fact that they approach the problem from the theoretical rather than the practical side, and without a sufficient acquaintance with those phenomena presented by the structure of the crust of the earth with which the modern school of stratigraphical geologists are so familiar. The long accepted theory that the earth consists of a mass of molten rock material covered over by a relatively thin shell or crust produced by the cooling of the surface was attacked by W. Hopkins in a paper read before the British Association in 1847, in which he endeavoured to prove from the phenomena of precession and nutation that the crust cannot be less than from 800 to 1,000 miles thick, and that it is probably much thicker even than that. The data on which he based his calculations were called in question by Delaunay, and even physicists themselves are no longer convinced that the argument derived from precession and nutation is either applicable or reliable.

Lord Kelvin (Sir William Thomson), arguing from the phenomena of the tides, insists that the earth is practically a solid body and that we may be quite certain that it is solid in the interior, and utterly rejects the idea that it can have a fluid interior, covered with a crust less than 600 miles thick. He maintains that, were the interior in a fluid condition and covered by only a thin crust, there would be no tides in the ocean, for the crust would be pulled upwards as well as the water, and there would be no relative displacement, and that, unless the earth were, as a whole, as rigid as steel, the tides would be only two-thirds of what they would be if the earth were perfectly rigid, and only two-fifths if it were not more rigid than glass, and says that we are forced to the conclusion that the earth is on the whole or in great part solid. The investigations hitherto made on the phenomena of the tides have not been sufficiently extensive or accurate to determine whether the crust is absolutely rigid or partially flexible, hence implicit reliance can hardly be placed in the arguments derived from them. The value of such theoretical conclusions on the part of the mathematical school is depreciated by the fact that the members of it differ among themselves, and Delaunay, Haughton, Henessey, Fisher, and Mallet have questioned on theoretical grounds the conclusions at which Hopkins and Kelvin have arrived, which shows that the application of mathematical formulæ to the solution of geological problems has not been decisive of the questions at issue. Theory may endeavour to prove that the globe is rigid and hence practically solid or possessing a crust of enormous thickness, but fact, as exemplified in the phenomena of volcanic eruptions and in the compression and contortion of the earth's crust, will unfortunately not conform to theory, and this want of conformity the theorist judiciously ignores when making his calculations. In support of his theory that the earth is practically a solid body, Kelvin attempts to trace the history of its consolidation by supposing that it was originally in a molten condition, and that on the cooling of its surface a crust was formed consisting of granite, which, as every geologist knows, is a plutonic and not a volcanic rock, and hence one that would never be formed by cooling at the surface. He quotes Bischof's experiments as his authority for believing that this crust would be denser than the liquid rock from which it had cooled, and in one of his papers quotes the estimated increase of density at about 10 per cent. and in another paper about 20 per cent.; but unfortunately it is not absolutely certain that it is denser at all, for the

experiments of Mr. Whitely of Leeds seem to show that dolerite (as well as iron, copper and brass) is less dense in the solid than in the liquid state. Assuming its greater density in the solid condition (which is probably correct), he proceeds to show that the solidified crust, being unable to sustain the strain of the attraction of gravity, would break into pieces and sink to the centre. He also endeavours to show that these successively formed and fractured crusts would ultimately, when they reached the centre, build up a series of piers of solid rock bridged over by large masses of the crust which had subsided upon and across them, forming roofs and giving rise to a gigantic kind of 'honey-combed' structure containing liquid rock material. He also supposes that these roofs would, from time to time, collapse, giving rise to earthquake shocks! But he entirely overlooks the fact that so soon as any portion of the solidified crust commenced to sink into the molten interior it would begin to be heated by it, and consequently diminish in density and cease to sink, and would soon assume the molten condition again before it had sunk far beneath the surface.

The frequent and long continued repetition of this process would ultimately reduce a surface layer of considerable thickness to such a temperature that a crust so thick might be formed as to sustain itself by its own rigidity, so long as resting on, and supported by, the liquid or viscid rock material below it. But, in whatever manner and under whatever conditions it was formed, there is a crust, and the use of the term implies a belief in something of a different nature underneath it; the reasons for believing that it is a liquid substratum will follow. But even supposing that the crust did continue to sink (in fragments) to a considerable depth without loss of density, it can hardly be imagined that it would ever reach the centre, where the pressure must be so intense as to forbid the idea of the material being in a molten condition though intensely hot, for we do know that pressure raises the melting point of certain substances very considerably, though we do not know to what extent; we do not know whether the rate of rise of the melting point is proportional to the rate of increase of pressure. We know that the density of the earth as a whole is about 5·6 and that the average density of the rocks forming the crust is about 2·5 or a little more, hence there must be at the centre or in a layer of uniform thickness surrounding it a vast quantity of matter of much greater density than that of the earth as a whole, probably consisting of metals

with an average density of about 8·5. It is impossible to believe that rock material of density 2·5 could sink through matter of density 8·5, or even that it could sink through matter that is at all denser than itself, hence the fragments of the crust would soon be arrested in their progress to the centre. Lord Kelvin assures us, however, that 'no possible degree of rigidity in the crust could prevent it from breaking in pieces and sinking wholly below the liquid lava'; it is, however, on the other hand, at least as certain that it would not sink relatively very far, much less (if that were possible) would it reach the centre to form a 'honey-combed' or any other kind of mass. The hypothetical nature of these speculations regarding the interior of the earth is seen in the fact that he also assures us 'it is however scarcely possible that any such continuous crust can ever have formed all over the melted surface at one time and afterwards have fallen in.'

Lord Kelvin attaches great importance to the question of tidal attraction and maintains that the existence of the tides proves conclusively that the earth as a whole must be a rigid body, otherwise the rocky crust would rise and fall as the ocean does under the attraction of the sun and moon. This seems to be conclusive, but it may be possible that the earth may have a large proportion of fluid material in its interior and still behave as a rigid body, owing to the rapidity with which it rotates around its axis. It was at one time maintained by Hopkins, and supported by Kelvin with equal confidence to that which he places in the argument from the tides, that were the earth fluid in the interior or even only so to a large extent, the precessional movement of the earth's axis would be much more rapid than it is, but the effect of the rapid rotation of the earth in causing it to behave as a rigid body, even though largely fluid, was not taken into account. When this was recognised from experiments made upon the rotation of hollow-bodies filled, or only partially filled with fluid, such as large hollow metallic spinning tops which spin and exhibit a precessional motion exactly as if they were entirely solid metallic bodies, it was seen that rapid rotation entirely neutralizes the effect that would otherwise be due to the body having a fluid interior—so far at least as such a slow motion as precession is concerned. Hence the argument derived from the phenomena of precession, that is, that it proved the earth to be solid was abandoned as being inapplicable to the case. May it not be possible that the rapidity of the earth's rotation may cause the fluid portion to behave as if it were perfectly solid under the

tidal influence of the attraction of the moon and sun, for at the equator it rotates at a speed of over 1000 miles an hour? The effect of rapid rotation is seen when a very soft felt hat is caused to rotate rapidly by blows applied to the rim with a stick; when a disc of thin paper is caused to rotate rapidly on an axis to which it is attached it resists pressure and blows as if it were a disc of steel. When an endless chain is passed over a drum and set in rapid rotation and then set free, it falls to the ground in the form of a perfectly rigid hoop and runs along the ground as if it were a circular ring of steel and only collapses when its rotation ceases.

From the preceding it is apparent that the physicist regards the earth as either almost or entirely solid, but this conclusion is based on hypothetical arguments that are of little value when opposed to the facts that the geologist can bring forward in support of his theory that if the earth is not molten to the core there is at least a substratum of molten rock extending everywhere beneath a comparatively thin crust. Volcanic activity as manifested in the outpouring of vast quantities of lava has occurred in almost every region on the face of the globe, hence we are led to infer that the lava has in each case emanated from a reservoir that is co-extensive with the surface above it and not from isolated centres supplying each volcanic vent. The quantity of these lavas is truly enormous; in North America they cover an area of 100,000 to 120,000 square miles in successive flows, which attain a thickness varying from 1,000 to 4,000 feet, and in India they cover, to a depth of from 2,000 to 3,000 feet, an area of about 200,000 square miles. In the north of Ireland they cover about 1,000 square miles to a depth of 400 to 800 feet, and about the same extent in Scotland; in central France there is a still greater volcanic area, and others occur in Hungary, Italy, Asia Minor, Australia, and New Zealand. Had these great outpourings of lava been each derived from its own subterranean reservoir of molten rock, it is inevitable that the vast quantities of material brought to the surface from below would have led to the sinking of the surface to fill up the vacuums thus produced, but instead of finding evidences of such depression, we find in almost every instance that areas of volcanic activity are also areas of elevation. It might be contended that the crust is so thick as to prevent subsidence from taking place, but the reasons for rejecting the theory of a very thick crust are most conclusive. We are therefore driven to the conclusion that extravasated lava is immediately replaced by the movement of

the general substratum of lava to take the place of that which is driven to the surface, and the remarkable uniformity in the lavas of the most widely separated localities also favours the theory of a continuous substratum. Were the crust so thick as the mathematicians would have us believe, 800 to 1,000 miles, it seems improbable that the lava could have reached the surface owing to the loss of heat by contact with the cool rock material of the crust causing it to solidify, and in addition to this difficulty, it is almost impossible to conceive of any force powerful enough to lift a column of lava 800 to 1,000 miles in height in a vertical direction. But even if we admit the possibility of the expulsion and elevation of such a vast column of lava without being cooled in its long upward journey, it can be explained only by the agency of one force, the pressure of a cooling and contracting crust which is the ultimate cause of all volcanic action. Were the earth practically solid and rigid, contraction would almost cease and the motive power which forces lava to the surface would be lost; were there only isolated lakes of molten rock distributed under the surface, the crust covering them would require to shrink and be depressed in order to supply the motive force to expel the lava, and it would of necessity shrink to fill the vacuum caused by its expulsion; but, as already stated, instead of depression, we have in almost all cases evidence of elevation. As regards the efficiency of contraction to cause the extravasation of lava, Cordier has calculated that a contraction of the crust to the extent of only 1 millimetre ($\frac{1}{25}$ of an inch) would be sufficient to displace and expel to the surface a quantity of lava equal to the total amount that has been poured out during 500 of the greatest volcanic eruptions. That this contraction has not ceased is proved by the volcanic eruptions of the present day, and though the present seems a time of comparative quietude, it may be only one of those recurrent periods when volcanic energy is temporarily quiescent.

The crust is in a continual state of oscillation, showing that it at least is not in a rigid condition; we have proofs of recent and considerable elevation as well as of depression in many parts of the globe, not sudden uplifts and downthrows by means of jerks and wrenches indicating a rigid crust, but the extremely gradual pulsations of a gently yielding shell resting upon an equally yielding substratum. Evidence of this excessively gentle motion is seen in the fact that faults of thousands of feet of vertical displacement have been developed across the course of an already existing

river without deflecting it from its channel or altering the direction of the drainage of the country. The displacement occurred at such an exceedingly slow rate as not to exceed that of the erosive power of the river and the rate of the denudation of the surface of the land on both sides of the ultimately gigantic displacement. Equally conclusive evidence of the slow movement of the crust is afforded by the development of a mountain chain across the course of a river. When we find, as we often do, a river cutting its way directly across a range of mountains we are apt to infer that the mountain was first in existence and that the river found its way through it by means of a cleft in the rocks formed by some 'convulsion of Nature.' Nature, however, was not convulsed, the mountain was so slowly formed by the compression, curvature, and uplifting of the strata that the river was able to saw its way down through them at as rapid a rate as they rose, and thus was able to maintain its original channel although a mountain was rising as a barrier across it. The process is exactly analogous to that of the sawing of a log of wood by a stationary circular saw against which it is pressed, the river is the saw, the mountain is the log of wood. But perhaps the most classic illustration of the pulsations in the crust of the earth is afforded by the three remaining pillars of the temple of Jupiter Serapis at Puzzuoli, on the Bay of Naples, which, after their submergence in the sea on the subsiding of the land on which they stand, were again elevated above the sea-level by the slowly rising land, but bearing on their weather-worn surfaces the evidence of their submergence, the perforations made by the marine molluscs which had attacked and bored their way into them while under water. It does not however follow that all such motion in the crust has been equally slow, for we have evidence of comparatively rapid uplifts in recent times—but these are on a small scale.

Were there no yielding substratum underneath the crust, contraction and tangential pressure would crush and fracture instead of crumpling and folding the strata, and were the crust as thick as the mathematicians insist that it must be, how is it possible to account for the complicated and comparatively delicate foldings produced in the process of mountain making? In mountain systems fold succeeds fold in parallel ridges until strata which, in the case of the Alps, extended over 200 miles when horizontal are crumpled by a series of seven folds so as to occupy only 130 miles, and in another case, a range in California, the strata are so compressed and folded in five parallel ridges as to occupy only

six miles in width instead of the 15 to 18 miles that they occupied before compression. Such compression and folding would be impossible in a moderately, not to speak of an enormously, thick crust, in the latter case mountain ranges would be of vastly greater width than they are and would assume the form of continental elevations rather than narrow ranges. It is impossible to fold a Brussels carpet, a hearth rug, or a piece of thick felt into the delicate pleats that can be produced on a piece of fine muslin, the latter bears about the same relation to the former that the thin bears to the enormously thick crust. The scale and character of these foldings and crumplings of the rocks seems to point to a crust whose thickness is neither 1,000 nor even 100 miles, but much more probably under than over a fourth part of the smaller figure. And as evidence that this supposed rigidity of the crust has not been of long geological duration, we have the fact that most of the great mountain systems of the world, the Alps, Pyrenees, Rocky Mountains, Andes, and Himalayas have been mainly upheaved in Tertiary times and even so late in some cases as the Quaternary.

The existence of a crust implies also the existence of a still liquid substratum underneath it, but the thickness of this, that is the depth to which it extends, we have no means of determining. It is one of those problems which may be appropriately handed over to the consideration of the mathematician and the physicist, but the imperfection of the data upon which their calculations are based will cause the conclusions at which they arrive to assume to a large extent a speculative character. It is generally admitted, however, that the liquid portion may very probably not extend to the centre, but that the enormous pressure to which the central portion of the earth is subjected by the outer portion, may have the effect of consolidating it even though the temperature may be so high as to fuse the most refractory of all known substances under ordinary pressure. If such is the case, then it is highly probable that the earth is a globe consisting of an outer thin, and still to some extent flexible, crust of no great relative thickness covering a liquid substratum of unknown depth which in its turn incloses a potentially solid but intensely hot core of metallic substances. It is still, however, worth remembering that this conclusion may contain some or much potential error, for after all we do not know what the condition of the interior of the earth really is, but this we do know, that the search after the truth is of infinitely greater value to us than any authoritative disclosure of the actual state of affairs could possibly be.

CHAPTER XV.

KANT'S HYPOTHESIS.

Kant's Hypothesis.—The Nebular Hypothesis now generally associated with the name of Laplace, who adopted and elaborated it in his splendid work, the 'Mecanique Celeste,' which takes rank second only to Newton's 'Principia,' was originally propounded by the great philosopher Kant. It is one of the grandest conceptions of the human intellect, for it attempts to solve the gigantic problem of the origin, not only of our earth and the other members of our solar system, but also of the other celestial bodies. It vastly enlarges our conception of the universe, and shows that the earth is not its centre but only an insignificant portion of a mighty whole to the other members of which it is allied by so many points of resemblance that are common to all as to demonstrate in the most conclusive way that it and the other bodies have all had one common origin. The researches of the chemist, the mathematician, and the physicist have all contributed to the confirmation of this magnificent generalisation. It does not, however, attempt to solve the inscrutable problem of the origin of matter, but starts with the assumption that all the solid, liquid, and gaseous matter in the sun, the earth, and the other planets and their satellites, as well as all the bodies distributed throughout illimitable space, existed at one time in the form of gas, the most diffused condition in which matter can exist. It supposes that this gaseous matter was not absolutely uniformly diffused through space, but that in some parts it was slightly more dense than in others. This difference need not necessarily have been great; it is sufficient that a difference, however minute, may have existed, in order to account for the commencement of concentration towards particular spots in obedience to the law of gravitation. Let us suppose that in the vast region of space of which our solar system is now the centre there existed, originally, a slightly denser distribution of this diffused gaseous matter in which was contained all the chemical elements which have been detected in its various members. The attraction of gravity would set up concentration towards the slightly denser portion; concentration would be followed by condensation, and this would result in the distribution of the matter in such a way that the denser

would occupy the centre of the shrinking mass, and the successively lighter and lighter portions would be distributed around this centre in their order of density. Now, we have assumed that there was a point where the diffused matter was denser than elsewhere; then, if the surrounding matter was not absolutely equally diffused around it on every side, the passage of the molecules of the heavier metals through those of the lighter substances on their way to the centre would give rise to a rotary motion in the whole mass which would increase in rapidity in proportion to the diminution in the bulk of the whole mass. The way in which water behaves when escaping by an opening in the bottom of a wash-hand basin illustrates the facility with which a rotary motion is developed in matter which is concentrating on all sides towards a central point. And as concentration and condensation proceeded at the centre the attraction of gravity towards it would increase and would ultimately overcome the attraction of gravity exerted by the outer portion, with the result that the inner portion would separate itself from the outer, which would be left behind in the form of a ring revolving around the central portion in the same direction as which it moved when forming a part of it. And supposing that the matter constituting this ring was not equally dense throughout, it would in turn commence to concentrate around any slightly denser portion until all the ring had condensed into a single mass, and a planet revolving around the main central mass and rotating in the same direction on its own axis would be formed. As concentration and condensation proceeded within this planetary mass, a ring would be formed around it in the same way as the ring was formed which gave its birth, and from its own ring another body revolving around it would be formed which would rotate on its own axis as well as revolve around the planet in the same direction as that in which the planet rotates and revolves around the central mass. We thus account for the origin of the satellites as well as their parents, the planets. In the same way we may account for each of the planets in succession, the most remote from the centre being formed first, the nearest being formed last, leaving ultimately in the centre of the solar system the great remaining mass of the sun. The sun is an incandescent body which is continually losing its heat by radiation into space, only an infinitesimal portion of which is intercepted by the planets. As it loses heat it contracts; its particles approach each other more closely, and as the energy due to their separation is less in the contracted than in the original state, and the energy cannot be

lost, it reappears as heat, and thus the heat is maintained apart from the heat developed by the impact of meteors upon it, which by themselves could not generate enough of heat to maintain the enormous temperature of the sun. It loses daily as much heat from every square foot of its surface as would be produced by the combustion of 20 tons of coal daily upon each square foot.

Now, all the planets, large and small, to the number of about 380, revolve around the sun and rotate around their axis in the same uniform direction, viz., from W. to E., and all the large and many of the small ones move in orbits nearly in the same plane, and all the satellites (with the exception of those of Uranus and Neptune) conform to the same law. In the case of the satellite of Neptune it revolves in a retrograde direction. viz., from E. to W., the points of the compass being determined on the supposition that we are looking down on the plane of the ecliptic from the north. The satellites of Uranus are a somewhat doubtful exception, for they revolve in an orbit that is almost vertical (82°) to the plane of the orbit in which Uranus revolves around the sun, to which fact their apparent retrograde motion may be due. They have but little motion that can be regarded as from E. to W., for if they revolved around Uranus as in a plane at right angles to the ecliptic then they would have none in either direction, and if their plane of revolution were deflected to only 1° or even a fraction of a degree beyond the perpendicular on the opposite side, then they would revolve in the opposite or normal direction. Their retrograde motion is therefore not of a very pronounced character.

It was when contemplating this wonderful uniformity in the motions of so many separate bodies that Laplace was led to infer that it could only have been due to their having had a common origin. According to the theory of chances there is but one chance in favour of this uniformity being due to accident, against a number so large that it would take sixty figures to represent it, in favour of its being due to a common cause. It is one of the most convincing cases of circumstantial evidence that could possibly be adduced and only falls short of actual proof. And this is only part of the evidence, for the shapes of the planets and satellites conform to their direction of rotation, their greatest diameters lying in the plane of their equators, their polar diameters (around which they rotate) being shorter, with the result that they are flattened at the poles, forming oblate spheroids, this being the exact form that unconsolidated material would assume when in rotation. Their densities also lend strong confirmation of

the truth of the theory in regard to the order in which they are believed to have been formed. There is a general increase of density from the outer to the inner planets, Neptune being, as compared with water, 1·1; Uranus, 1·2; but Saturn is an exception, being only ·72; Jupiter, 1·3; Mars, 4·17; the earth is another exception, being 5·6; while Venus is only 4·8; Mercury is 12·4. The sun itself is only 1·4, the nearest approach to it being Jupiter. In both consolidation has not yet taken place, for, like the sun, Jupiter is still in the act of cooling, and his red-hot fiery nucleus is sometimes seen during disturbances in the atmosphere by which he is surrounded.* The violence of these disturbances may be estimated from the fact that the 'clouds' have been seen to travel 200 miles in an hour. The asteroids or planetoids are supposed to have been formed out of a vast ring of nebulous matter which was broken up into small masses by the attraction of the mighty mass of Jupiter, inside of whose orbit they revolve around the sun.

In their respective distances from the sun there is the most striking evidence of the existence of law being in operation when the nebulous matter was successively left behind as rings by the gradually contracting and condensing mass, for each planet in succession, as we pass from the outer Neptune towards the sun, is approximately half of the distance of the one beyond it. This is doubtlessly due to the increasing density of the mass after each successive ring was shed off and left behind, and in the regularly progressive increase of the velocity with which each planet in succession nearer to the sun revolves around it we have strong reasons for believing that each of these bodies once formed part of a condensing and shrinking mass of matter. And apparently as a corollary to this, the year of the outer planet is the longest, and each in succession nearer to the sun has a shorter and shorter year as compared with that of our earth. We have thus seen that, as regards no less than six different conditions, viz., (1) direction of revolution and rotation, (2) shape, (3) density, (4) distance, (5) velocity, and (6) length of year, there is overwhelming evidence in support of the Nebular Hypothesis as an explanation of the origin of our solar system. These are all conditions developed in the process of their evolution, but when we come to the consideration of the composition of members of our solar

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* Others, however, regard the red colour and the 'red spots' as merely lower layers of vapour and not as the surface of a molten globe.

system and of the other celestial bodies it seems scarcely possible to doubt that they have all been formed from one vast storehouse of homogeneous matter out of which they have been differentiated.

Meteorites are solid bodies which from time to time fall upon the earth, but the reality of such occurrences was long doubted, and the accounts given by those who asserted that they had seen them fall were treated with ridicule. At last it became no longer possible to doubt these statements, and the question entered upon a new phase when, in 1802, a paper by Edward Howard, giving the results of a chemical and mineralogical examination of four of these bodies, was read before the Royal Society of London, in which he expressed his conviction that they were not terrestrial bodies and bore no resemblance to ordinary mineral substances. This paper attracted the attention of scientific men in France, who had soon an opportunity of investigating the matter for themselves, for in 1803 a fall of meteorites, estimated at between two and three thousand, took place near L'Aigle, Orne. A Government investigation took place, and the result of the report was that it was no longer possible to doubt that a fall of extra-terrestrial bodies had taken place. Various views as to their origin had previously been held; they were supposed by some to have been ejected from the sun, by others from terrestrial or lunar volcanoes, or that they had been formed as concretions in the atmosphere, or that they were ordinary stones which had been struck by lightning or which had been carried into the air by whirlwinds. They are now almost universally admitted to be neither solar, lunar, nor terrestrial in origin, but to be derived from inter-stellar space, from which they are attracted by the earth when its path crosses theirs. They differ in appearance and also in many points in their mineral composition from the mineral and rock substances forming the crust of the earth. They are of high specific gravity, varying from 2·7 in the case of the stony ones to 7·5 in the highly metallic, that of ordinary rocks varying from 2·6 to 3·5. They are usually dark or even black on the surface, on which there is generally a glazed crust showing signs of fusion due to the heat generated by friction in their rapid passage through the atmosphere, which is estimated to be at the rate of from 10 to 45 miles when entering it, but this is speedily reduced to about three miles by the resistance of the atmosphere. The highly metallic ones show in the interior a rudely crystalline structure suggestive of slow cooling in the interior of a larger mass, and the stony ones have internal "slicken-sided" surfaces that seem to indicate their

having formed part of a larger mass that had been subjected to contortion like many of the rocks and minerals in the crust of the earth.

Meteorites have been classified, according to their composition. into three classes—(1) Siderites, consisting chiefly of nickeliferous iron with schreibersite, troilite, graphite, &c.; (2) Siderolites, consisting of sponge-like nickeliferous iron with silicates in the



Fig. 103. Siderite, found at Cranbourne, near Melbourne, Australia; weight $3\frac{1}{2}$ tons.

(*From a Photograph by J. C. Christie, from the original in the British Museum.*)

cavities, constituting a partially stony mass; (3) Aerolites or stony meteorites, consisting mainly of silicates with particles of nickeliferous iron, troilite, &c., disseminated through the mass. Now, though meteorites contain no elements that have not been found to occur in the crust of the earth, they contain many mineral compounds that have not yet been discovered elsewhere, such as schreibersite, troilite, oldhamite, osbornite, daubréelite, lawrencite, asmanite, maskeleynite, and peckhamite. These are chiefly

metallic compounds in which iron, nickel, magnesium, calcium, and aluminium occur most frequently, the first two being most abundant, and titanium, chromium, manganese, cobalt, arsenic, antimony, tin, and copper occur less frequently, or in smaller quantities. They occur chiefly as sulphides, but phosphides and protochlorides also occur, and several new forms and compounds of silica. Numerous other minerals occur which are found also



Fig. 104. Siderite from Tucuman, Argentine Republic, S. America ; weight, 1,400 lbs.

(*From a Photograph by J. C. Christie, from the original in the British Museum.*)

in the crust of the earth, but quartz, the commonest and most abundant of terrestrial minerals, is conspicuous by its absence. The nature of many of these new compounds that are peculiar to meteorites is such as to forbid the idea of the possibility of their having been formed, or of their remaining undecomposed, under circumstances in which air or water were important factors.*

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* For further information on this most interesting subject, the student is referred to the admirable 'Introduction to the Study of Meteorites,' by Mr. L. Fletcher, F.R.S., Keeper of the Minerals at the British Museum of Natural History, South Kensington, London, S.W. (to which it is one of a series of most excellent popular guides), price 3d., postage 1½d.

The facts already mentioned seem to indicate that only the conditions under which meteorites were formed, and not the elements entering into their composition, were different from those prevailing in the earth, for, as the accompanying table shows,

Table of Terrestrial Elements, showing their occurrence in Celestial Bodies. The sign × means present; ? doubtful; and the numbers, in the case of Meteorites, indicate the order of their importance.

Elements.	Meteorites.	Sun.	Stars.	Comets.	Nebulæ.
Aluminium	10	×			
Antimony	22		×		
Arsenic	21				
Barium		×	×		
Beryllium	?	×			
Bismuth			×		
Boron					
Bromine	?	×			
Cadmium		×	×		
Caesium					
Calcium	9	×	×		
Carbon	5	×	×	×	×
Cerium		×			
Chlorine	13	×			
Chromium	18	×	×		
Cobalt	20	×			
Copper	24	×			
Didymium		×			
Erbium		×			
Fluorine	?	×			
Gallium		×			
Gold					
Hydrogen	11	×	×		×
Iodine		×			
Iridium		×			
Iron	1	×	×	×	×
Lanthanum		×			
Lead	?				
Lithium	14	×			
Magnesium	8	×	×	×	×

Elements.	Meteorites.	Sun.	Stars.	Comets.	Nebulæ.
Manganese	19	×	×	×	×
Mercury			×		
Molybdenum	?	×			
Nickel		×			
Niobium		×			
Nitrogen	12				
Osmium		?			
Oxygen	6	×			
Praesodymium					
Palladium		×			
Phosphorus	3				
Platinum		?			
Potassium	16	×			
Rhodium		×			
Rubidium		?			
Ruthenium		?			
Selenium	?				
Silicon	7	×			
Silver		×			
Sodium	15	×	×	×	
Strontium	?	×			
Sulphur	4				
Tantalum		?			
Tellurium		×	×		
Thallium					
Thorium		?			
Tin	23	×			
Titanium	17	×			
Tungsten		?			
Uranium		?			
Vanadium		×			
Yttrium		×			
Zinc	?	×			
Zirconium		×			

*** For the above table which I have constructed, I make no claims of absolute accuracy. Its purpose will be served if it indicate in a graphic manner the community of matter among the celestial bodies and our Earth.

out of the 64 elements which are here assumed as the number entering into the composition of the earth's crust, the presence of no less than 24 has been determined by chemical analysis in meteorites, and there are other nine in addition, of which traces are said to have been found, but whose occurrence is regarded as doubtful. The method of direct chemical analysis is, of course, inapplicable to the other celestial bodies, seeing that we are unable to obtain portions of them for examination, but with the aid of the spectroscope a great number of the terrestrial elements have been found in them also, and no new elements, with the

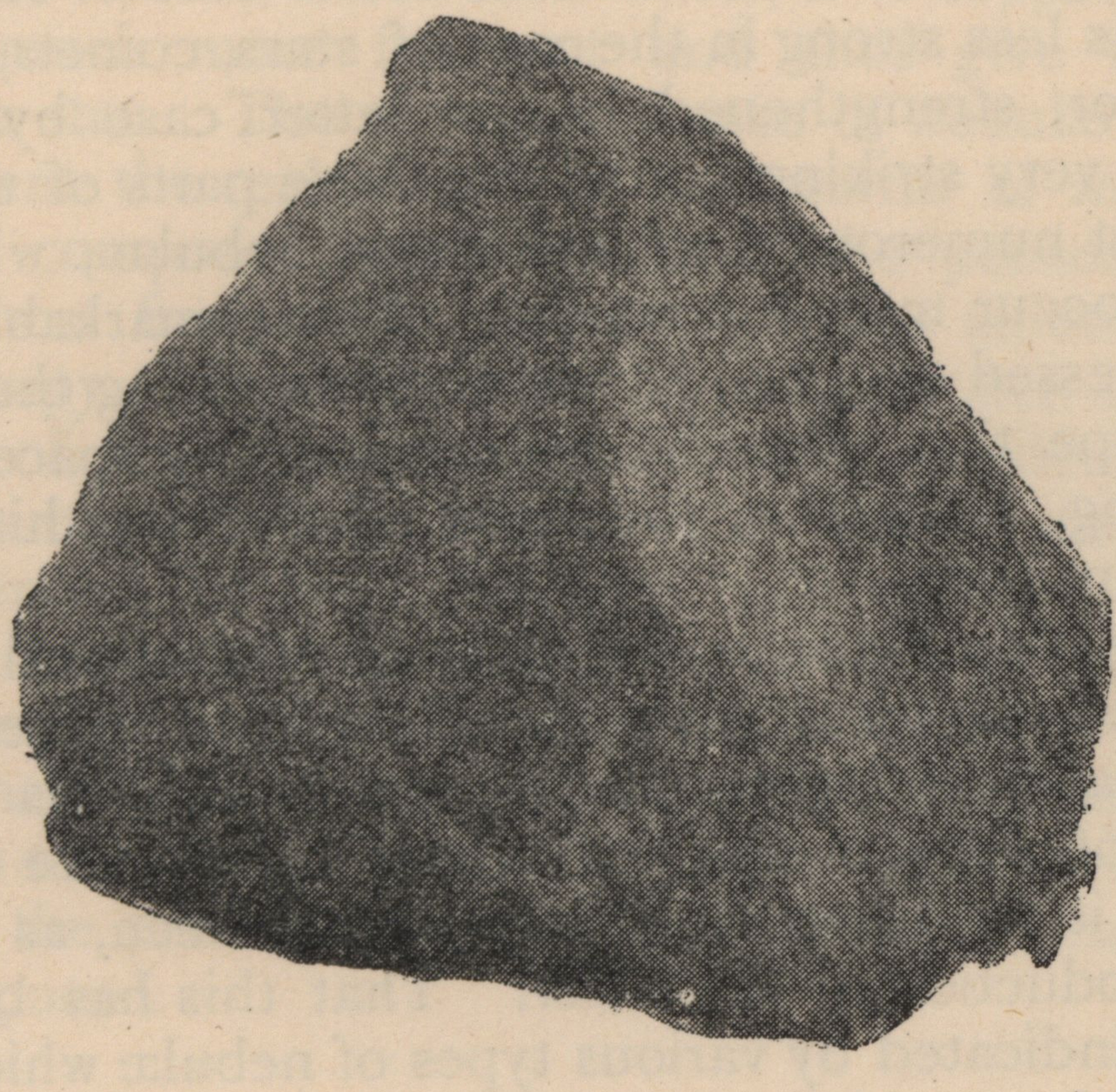


Fig. 105. Siderolite from Imilac, Desert of Atacama, S. America.

(*From a Photograph by J. C. Christie, from the original in the British Museum.*)

exception of the helium of the solar prominences and the coronium of the corona, that are not known to occur in the earth. Thus of the 64 the sun contains 42, and eight more which are doubtful, and only 14 are wanting in the sun of all those occurring in the earth, and of these 14 that are wanting five occur in meteorites. In meteorites 24 occur and nine are doubtful. There are 19 that occur both in sun and meteorites, and there are 47 that occur in either (including the 19 that occur in both), and 57, if we include the doubtful ones of both, in which case there are only seven elements wanting between sun and meteorites

of the 64 which constitute the crust of the earth. More conclusive circumstantial evidence of the community of origin of sun, earth, and meteorites it would be impossible to find, and the strength of this evidence is fortified by that derived from the stars, comets, and nebulæ. There are 14 elements which have been directly detected in the spectra of the stars,* five in the nebulæ, and five in comets. Carbon and magnesium have been found in all the five celestial bodies—sun, meteors, stars, comets, and nebulæ. Iron, hydrogen, and manganese in four, and lead in three of them.

The evidence afforded by chemical composition in regard to identity of origin is most conclusive in the case of sun, earth, and meteors; it is less strong in the case of stars, comets, and nebulæ. It is, however, strengthened in the latter case by evidence of another and very striking kind. In those parts of the sky where stars are most numerous there are fewest nebulæ; where stars are few, nebulæ occur most frequently. This remarkable fact was so forcibly impressed on Lord Rosse when sweeping the sky with his great telescope that, when he came upon any space where stars were awanting, he was in the habit of warning his assistant to 'prepare for nebulæ.'

This connection between the absence of stars and the presence of nebulæ and *vice versâ* was so apparent as to suggest to Laplace the idea of cause and effect, and to lead to the idea that stars are formed out of nebulæ and that where nebulæ are wanting and stars present it is due to the former having been, as it were, used up in the production of the latter. That this has been the case seems to be indicated by various types of nebulæ which show what appear to be the transition stages between nebula and star; some of them show only a faint nebulosity, some have indications of a faint nucleus that is just discernible, in some the nucleus is easily seen, and in others the nucleus is a brilliant star-like point. The intermediate stages in the passage of a nebulous star into an ordinary one can also be traced in a few graduated stages in which each closely resembles the stage that is considered to precede and that which is considered to follow. The nebulæ in the Pleiades take the form of long lines or wisps on which stars occur as if they were beads threaded on a string, and recent photographs of

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* But since some stars have precisely the same kind of spectrum as the sun, it might safely be said that all the elements which have been detected in the sun exist also in stars.

Cygnus in the Milky Way show long straight and curved lines of nebulæ with condensations on them. Where two lines or sheets of nebulæ intersect each other, a bright star is invariably seen. This is strictly in accordance with the Nebular, and equally so with the Meteoritic Hypothesis which has recently been elaborated and worked out by Lockyer from a suggestion originally made in 1871 by Thomson (now Lord Kelvin) and Tait. According to the Meteoritic Hypothesis as propounded by Lockyer, comets, nebulæ, and those stars which give a spectrum of bright lines, and also those with bright lines and dark flutings, consist not of glowing gas but of swarms of meteorites coming continually in collision. Where lines or sheets of nebulæ cross each other, it is supposed that the collisions are much more frequent and thus give rise to the appearance of a star. The apparent shapes of nebulæ may therefore not represent the real shapes of the swarms of meteorites of which they are composed, but only that of the portion where the collisions are most frequent in proportion to the amount of space which they occupy. The Meteoritic Hypothesis then accounts for the formation of stars by the concentration, condensation, and ultimate amalgamation of vast swarms of meteorites into one mass. The heat generated by their frequent collisions may have been sufficient to fuse all the materials of which they were composed, and thus to permit the heaviest of the constituents to seek the centre of the mass while it was still in a fluid condition, but this hypothesis fails to explain how these meteorites were formed and to account for the pre-existing condition of the matter of which they were composed.

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In most cases, the matter falls, but in some cases the matter is thrust up; in this case the crack is called the thrust plane

Wave

Height = 40 feet. (3' or 6' round coast)
width 100 feet & 10,000 feet.
Equator 85° or 86° F.
Sub-trop 60° and 80°.
Temper 50° to 60°.
Polar 0° etc.

Stage.

Tellurie Lines due to absorbtion of air.
Tuning fork.

Fraunhofer lines
Telluric lines

Schehallien

Mountain

Pendulum Observations

Balance.

Cavendish's Experiment

11.2 ~ 5.212

